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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

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THE REFLECTING POWER OF THE ALKALI METALS

By J. B. NATHANSON

I. INTRODUCTION

The alkali metals, by virtue of their great chemical activity and their interesting electrical and optical properties, afford interesting fields for research. The great difficulty in handling the metals has, however, limited their investigation. Further interest in these metals has been added by the comparatively recent study of the selective photo-electric effect which, it has been suggested, might be due to the peculiar optical properties of the alkali metals in the region of the selective effect. If such be the case, there ought to be a marked change in the reflecting powers of the alkali metals in this region. Consequently any knowledge of the reflecting powers of the alkali metals as a function of the wave-length and plane of polarization is highly desirable, and it is to this end that the present investigation has been carried out.

Up to the present no direct method has been employed in the study of the reflecting powers of the alkali metals. All our knowledge rests upon the comparatively few katopric measurements. The first investigation was made by Paul Drude[1] upon the single metal sodium. The reflecting surface was formed by melting the

[1] *Annalen der Physik*, 64, 159, 1898.

sodium in a vacuum, and the reflecting power obtained from a study of the nature of the reflected elliptically polarized light.

In 1913, R. W. and R. C. Duncan[1] made a more extended investigation of the optical properties of sodium and potassium as a function of the wave-length. Drude's method was employed. The metals were used in the form of mirrors, i.e., glass backed by metal. These authors found very high values for the reflecting powers of sodium and potassium, the former being the better of the two.

In the present investigation the reflecting powers have been obtained by a direct measurement of the incident and reflected light-intensities. A photo-electric cell was used as a photometer, the cell being previously calibrated in terms of known light-intensities. This use of the photo-electric cell has been anticipated by E. V. Hulburt,[2] whose work appeared during the progress of this investigation. Hulburt determined the reflecting powers of a large number of metals for ultra-violet light, the angle of incidence being kept constant. It appears that Hulburt assumed a linear relation between the photo-electric current and the light-intensity, an assumption which does not seem to be justified in view of this and other investigations.

II. WHITE, UNPOLARIZED LIGHT: RELATION BETWEEN THE PHOTO-ELECTRIC CURRENT AND THE LIGHT-INTENSITY

The apparatus.—In the present investigation of the reflecting power of the alkali metals, a photo-electric cell was employed as a photometer. The cell chosen was one of the most sensitive ones made by Dr. Jakob Kunz of this Laboratory. The cathode consisted of rubidium deposited by distillation upon a film of silver. The anode consisted of a loop of platinum wire. Between the anode and cathode is located a platinum guard ring which is usually earthed to avoid leakage across the glass between the electrodes.

Investigations on the relation between the photo-electric current and the light-intensity are not in good agreement with each other. While Elster and Geitel[3] and Richtmeyer[4] have shown

[1] *Physical Review*, **36**, 294, 1913.

[2] *Astrophysical Journal*, **42**, 205, 1915.

[3] *Annalen der Physik*, **48**, 625, 1893.

[4] *Physical Review*, **29**, 71 and 404, 1909.

that the photo-electric current is strictly proportional to the light-intensity, on the other hand Lenard[1] and quite recently Ives[2] have shown that the linear relationship does not strictly hold. Ives, in an extended investigation of the subject, wherein he subjected a great variety of cells to different conditions, showed that the relation is not a linear one, but that the photo-electric current is a complicated function of the voltage, electrode distance, and gas pressure in a cell.

Consequently, owing to the conflicting literature on this subject, it was decided, before using the cell above as a photometer, first to calibrate it in terms of known light-intensities by the aid of crossed nicol prisms. To this end, the arrangement of apparatus shown in Fig. 1 was employed.

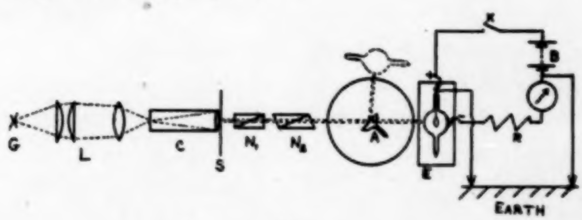


FIG. 1

A Nernst glower G was used as a source of light, both on account of its intensity and because of its reputation for constancy. The light after passing through several condensing lenses L is focused upon the circular aperture of the collimator lens. The light then passes through the nicols N_1 and N_2, the former having rectangular ends to eliminate rotation of the beam when N_1 is rotated.

The circular beam of parallel rays of light is then incident upon the photo-electric cell, which is inclosed in the earthed metallic box E. This box was air- and light-tight, and blackened on the inside. It served to eliminate any possible extraneous light. In this box was placed some phosphorous pentoxide to render the air dry and so to diminish leakage across the glass or across the hard rubber disks through which were conducted the wires leading to the electrodes of the cell. The beam was admitted through a glass

[1] *Annalen der Physik*, **8**, 149, 1902.

[2] *Astrophysical Journal*, **39**, 428, 1914; **43**, 9, 1916.

window, before which was placed a shutter sliding on a groove, so that by means of a cord and pulleys the shutter could be easily raised or lowered by the observer at his observing station.

The voltage used across the photo-electric cell varied from 111 to 134 volts, this being furnished by a set of constant potential cells. As a detector of the photo-electric current, a sensitive galvanometer was employed, being loaned to the writer by the Department of Astronomy through the kindness of Professor Joel Stebbins. This galvanometer had a figure of merit of 5×10^{-10}. The terminal of the galvanometer next to the negative pole of the battery was earthed. This was found to be highly essential, serving to eliminate completely troublesome leakage currents in the circuit, and enabling one to take observations with the greatest accuracy in the most humid days of the summer.

Method of observation.—With the axes of the nicols parallel to each other, the cell was exposed to the light and the galvanometer deflection observed. Then the deflection was observed for some angle between the nicols. Finally, the nicols were made parallel again, and the deflection again observed. This last observation served as a check on any fluctuations of the light-intensity that might have occurred during the observations. As a matter of fact, the light-intensity was absolutely constant only on rare occasions, there being usually a small and slow variation. However, by continual checking of the deflection for zero angle between the nicols, proper corrections could be applied to the deflection for any angle between the nicols.

Several readings were always taken for each position of the nicols. The individual readings usually agreed to within two- or three-tenths of a millimeter for the larger deflections, and to a correspondingly smaller extent for the smaller deflections.

The results.—In Fig. 2 are given the deflections corresponding to various light-intensities, the latter being proportional to the squares of the cosines of the angles between the two nicols. Each deflection is the average of two to four observations.

Upon examination of the plotted results, it is evident that the current light-intensity relation is *not* a strictly linear one, but is in the form of a curve slightly concave toward the illumination-

axis. The results for the curve labeled 130 volts were obtained by using a different quadrant of the nicol prism, N_1; the light

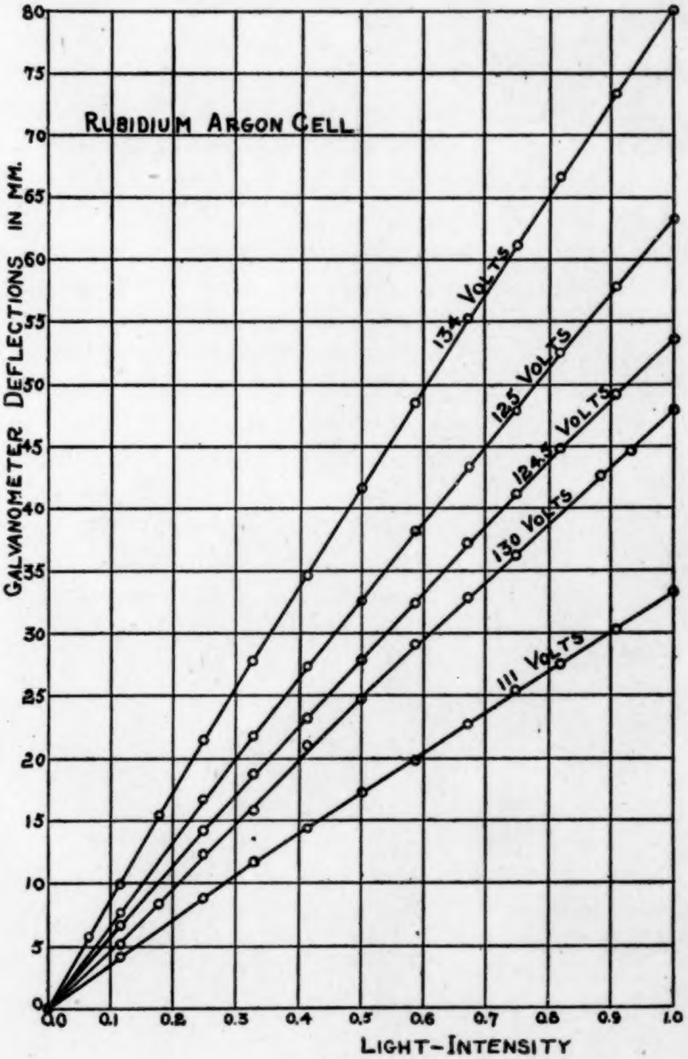


FIG. 2

also was somewhat weaker than in the other three cases, whence the smaller deflections. This serves to show that the concavity of the curves cannot be due to lack of symmetry of the nicol prism. This

concavity increases, the larger the range of the deflections. In the succeeding determinations of reflecting powers, proper corrections were always made in accordance with these curves.

III. PREPARATION OF THE ALKALI MIRRORS

The alkali mirrors were made either by distillation or by pouring the metal upon a square piece of plane glass about 2.5 cm on edge and 1.74 mm thick. The cell C was made by joining a small piece of glass tubing to a much wider piece. The latter was then cut off, leaving a bell-shaped opening. The edge of this bell was ground plane with emery and finally with rouge, the edge becoming highly polished. The glass plate, after being thoroughly cleaned with alcohol, potash, and nitric acid, was then clamped tightly against the polished edge of the bell, and "Rock Cement" applied thickly around the edge P. The bell was then placed in an electric oven, and baked at about 140°C. Usually three applications of cement were applied to the cell. The baking was continued until the cement turned to a brownish color. This cement served excellently in making the cell air-tight, and in enabling one to subject the cell to much heat during the distillation of the metal, without endangering the vacuum.

FIG. 3

The cell was then attached to the glass apparatus shown in Fig. 3. In the case of Na and K, the metal was introduced into A through D, which was then sealed off, and the tube evacuated. The metal was then melted down with an electric coil. Great care is necessary in this process, as the glass is likely to crack very easily when the molten metal bursts out of its oxide skin.

A portion of the metal was poured into B, and from there distilled to H. A small molten globule was then guided to the concavity F. In this process the tube was removed from the pump, and the globule guided to F by means of successive jars by the hand. The metal was then distilled against the glass plate which was placed in contact with a flat piece of ice. The metallic vapor thus deposited itself upon the plate in the form of a mirror,

the layer of metal being made thick enough to be entirely opaque to light. The mirror was then sealed off and removed at *E*.

In the case of one of the K mirrors (mirror No. 2), a large amount of the metal was collected in *H* by distillation, and the whole molten mass forced into the cell against the glass plate, making a mirror out of a solid cake of the metal.

Rubidium cannot be obtained on the market in metallic form, and so had to be obtained by reducing RbCl with Ca, the materials being placed in an iron boat inclosed in a hard glass tube attached to *D* of Fig. 3. The metallic vapor was condensed in *A* before it was redistilled and deposited upon the glass plate.

Success in making the mirrors was not always attainable, there being many opportunities for failure in the long process. Many of the mirrors after being formed were found to have thin oxide films on their surfaces, and so were discarded. Only those mirrors were picked for investigation which appeared perfect as viewed by the eye.

IV. ARRANGEMENT OF APPARATUS FOR THE DETERMINATION OF THE REFLECTING POWER

In the determination of reflecting powers the arrangement of apparatus shown in Fig. 1 was employed, the nicol prisms being, however, removed so that the light incident on the mirrors was unpolarized. The metallic box containing the photoelectric cell was mounted upon the telescope arm of the spectrometer to facilitate the movement of the cell for any angle of incidence desired.

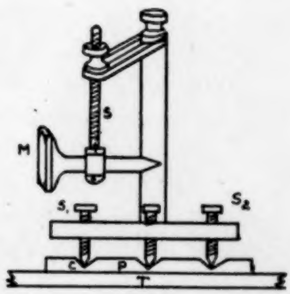


FIG. 4

The mirror *M*, Fig. 4, was mounted on a small tripod, whose legs fitted into cups *C* on a brass plate *P* which could be permanently clamped to the top of the spectrometer table *T*. The center of the reflecting face of the mirror was adjusted to lie along the axis of the spectrometer. After proper adjustment the plate *P* was clamped to the table *T*. By this means the mirror could be removed from the spectrometer table and quickly replaced in its original position.

This was found desirable, since, in the determination of reflecting powers, observations on the unreflected beam were alternated with observations on the reflected beam. Using this method of observation proper corrections could be made in case the light-intensity, or voltage across the photo-electric cell did not remain absolutely constant.

V. THE FORMULA

The ratio of the reflected light-intensity to the incident light-intensity gives the reflecting power of the whole mirror, i.e., metal plus glass. The greater interest lies in the reflecting power of the metal itself when in contact with the glass. Knowing this, it is possible to form a very close approximation as to what the reflecting powers of the metals would be in a vacuum.

Owing to the large number of internal reflections, the following mode of reasoning will be used to determine the reflecting power of the metal. Let

I = the light-intensity of the incident light
i = angle of incidence
r = reflecting power of the front face of the glass, i.e., the fraction of the incident light, incident on the glass, which is reflected back into the air
r' = reflecting power of the interior glass surface, i.e., for light internally reflected, e.g., as at C, E, and G
t = transmission power of the glass plate for a given thickness, i.e., the fraction of the light which, e.g., after penetrating the surface at A, reached the point B
R = reflecting power of the alkali metal, i.e., the fraction of the light incident on the metal glass boundary at B, for example, which is reflected by the metal.

The quantities r, r', t, and R are functions of the angle of incidence.

The sum of the components of reflected light-intensities, a, b, c, d, etc., are given by the series

$$O' = Ir + I(1-r)(1-r')t^2R(1 + r't^2R + r'^2t^4R^2 + r'^3t^6R^3 + \ldots).$$

The photo-electric cell registers the sum of all these components of the reflected light-intensity. If $O=\frac{O'}{I}$ is the reflecting power of the whole mirror (metal plus glass), then

$$O=r+\frac{(1-r)(1-r')t^2R}{1-r'Rt^2}.$$

Hence

$$R=\frac{O-r}{t^2(1+Or'-r-r')}. \qquad (1)$$

This is the formula that was employed in the determination of the reflecting power of the alkali metals. It will be noted that in order to know R the optical properties of the glass plates used in these mirrors must be determined.

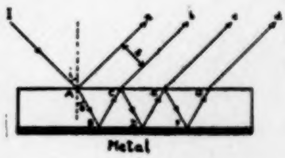


FIG. 5

Inspection of Fig. 5 shows that the beam after reflection is spread out. If S is the lateral displacement between two successive components, then applying Snell's law it follows that

$$S=\frac{t \sin 2i}{\sqrt{n^2-\sin^2 i}} \qquad . (2)$$

where t = thickness of the glass = 1.74 mm
i = angle of incidence
n = 1.5155 = index of refraction

This was determined by means of the Abbe refractometer, using the method of grazing incidence.

Taking i as 60°, the value of S is 1.26 mm. Theoretically, an infinite number of internal reflections occur between the metal and the air-glass boundary. Practically, the components of the reflected beam after the fourth one are negligible. Hence, taking four components as effective, the displacement would be about 5 mm. Adding 3 mm for the width of the beam, the breadth of the reflected beam does not exceed 8 mm. The aperture to the photo-electric cell was almost 2 cm, hence all effective components of the reflected beam were certainly able to enter the cell.

VI. OPTICAL PROPERTIES OF THE GLASS PLATES

In order to determine r, the reflecting power of the front face of the glass plate, the back face was abraided with coarse emery and then coated with lamp-black. The results are shown in Fig. 7, where the continuous line represents the experimental values, while the dotted line gives the theoretical values as given by Fresnel's reflection equation for natural white light.

The experimental values, which at first are smaller than the theoretical values, are, however, larger than the latter for larger angles of incidence. This may be due to a possible slight specular reflection of the abraided rear surface which becomes more effective for the larger angles of incidence. In general, the agreement is quite satisfactory, and demonstrates the adaptability of the photo-electric cell as a photometer.

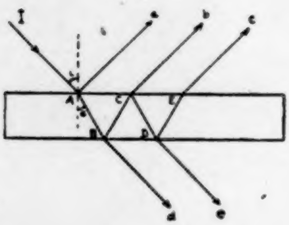


FIG. 6

Determination of t and r'.—The determination of the transmission power and the reflecting power of the internal surface of the glass was effected through a study of the light reflected and transmitted by the glass plate.

Following the method of reasoning employed previously, and adding up the components a, b, c, etc., of the reflected light, we have (see Fig. 6)

$$R'=r+(1-r)(1-r')r't^2+(1-r)(1-r')r'^3t^4+\ \ldots\ +\ \ldots$$

where R' is the reflecting power of the glass plate (both surfaces).

$$R'=r+(1-r)(1-r')r't^2(1+r'^2t^2+r'^4t^4+r'^6t^6+\ \ldots\ ).$$

Hence

$$R'=r+\frac{(1-r)(1-r')r't^2}{1-r'^2t^2}. \qquad (3)$$

Considering the light transmitted by the plate, and summing up the components, d, e, etc., we have for the total fraction, T, of the light transmitted,

$$T=(1-r)(1-r')t(1+r'^2t^2+r'^4t^4+\ \ldots\ ).$$

Hence

$$T=\frac{(1-r)(1-r')t}{1-r'^2t^2}. \tag{4}$$

Combining equations (3) and (4)

$$\frac{R'-r}{T}=r't. \tag{5}$$

Solving for t and substituting in equation (4), and then solving for r',

$$r'=\frac{(R'-r)(1-r)}{T^2+(R'-r)(1-R')} \tag{6}$$

and

$$t=\frac{T^2+(R'-r)(1-R')}{T(1-r)}. \tag{7}$$

Experimentally, R' is obtained by determining the intensity of the reflected light. Keeping conditions the same, T is obtained by merely swinging the cell around on the spectrometer to catch the transmitted light.

The results for R', r', t, and r are plotted in Fig. 7. The values of r' are somewhat lower than those for r, except for values of the angles of incidence approaching the critical angle for the glass plate, when r' crosses r and would ultimately reach 100 per cent for values of the angle of incidence of 41°. It must be borne in mind that the values of the reflecting powers shown in Fig. 7, and in succeeding tables and curves for white light, have been corrected in accordance with the calibration-curves of Fig. 2. By setting up a simple proportion between observed values of the galvanometer-deflections for the unreflected and reflected beam, and values of galvanometer-deflections on the calibration-curves, it has been possible to obtain the corrected values of the reflected light-intensity directly from the calibration-curves. The corrections are of course rather small.

VII. REFLECTING POWERS OF POTASSIUM, SODIUM, AND RUBIDIUM

Three potassium mirrors were investigated. In Table I is given a summary of the results. Mirrors No. 1 and 3 were formed by distillation, while No. 2 was formed by pouring the molten metal

against the glass and allowing it to solidify. The latter method was rendered quite difficult by the tendency of the metal to crystallize upon solidification.

The agreement between the reflecting powers for the different mirrors is indeed quite satisfactory considering that the mirrors

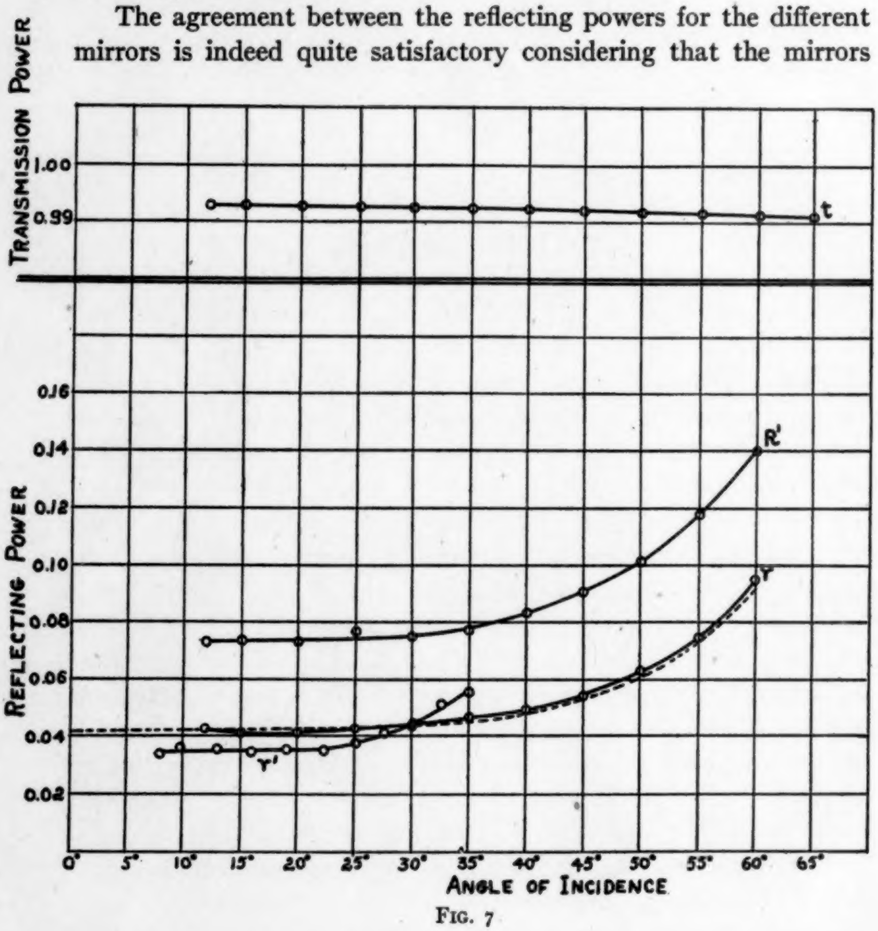


Fig. 7

were made at different times and under different circumstances. Especially is the agreement between mirrors Nos. 1 and 2 to be noted, the former being a distilled mirror, the latter being the "solid" metal mirror. This excludes any doubts that the metallic layers of the distilled mirrors were not thick enough.

The variation of the reflecting power with the angle of incidence is shown in Fig. 8. The reflecting powers increase very slowly

with the angles of incidence. Owing to refraction through the glass plates, the actual angles of incidence on the metal are of course less than those on the whole mirror, so that the curves for

TABLE I

POTASSIUM

O					R				
Angle of Incidence	No. 1	No. 2	No. 3	Mean	Angle of Incidence on Metal	No. 1	No. 2	No. 3	Mean
13°.5	0.8675	0.869	......	0.868	8°52′......	0.876	0.878	......	0.877
15	.870	.8685	0.865	.868	9 50......	.8805	.8795	0.875	.8785
20	.869	.869	.8645	.8675	13 3......	.8805	.8805	.876	.879
25	.8675	.8805	.8685	.872	16 12......	.880	.8925	.8805	.8845
30	.888	.873	.875	.8785	19 16......	.900	.8845	.887	.8905
35	.8695	.8835	.863	.872	22 14......	.8815	.8965	.876	.8845
40	.885	.880	.858	.8745	25 6......	.898	.892	.869	.8865
45	.872	.880	.860	.8705	27 49......	.8845	.8925	.872	.883
50	.885	.887	.8685	.880	30 22......	.897	.899	.881	.8925
55	.879	.875	.8645	.873	32 43......	.890	.887	.877	.8845
60	0.874	0.880	0.8715	0.8755	34 51......	0.8825	0.890	0.8805	0.8845

R are "shrunk" to the left. The critical angle for the glass is the maximum that could ever be reached using glass plates.

Much greater difficulty was experienced in obtaining a good sodium mirror than in obtaining a potassium mirror, because of

TABLE II

ANGLE OF INCIDENCE	O		ANGLE OF INCIDENCE ON METAL	R	
	Sodium	Rubidium		Sodium	Rubidium
13°.5............	0.8845	0.750	8°52′............	0.895	0.756
15............	.882	.757	9 50............	.895	.764
20............	.8825	.7575	13 3............	.8935	.765
25............	.8845	.7505	16 12............	.8975	.758
30............	.8785	.755	19 16............	.8915	.7625
35............	.8945	.755	22 14............	.9075	.762
40............	.8925	.7575	25 6............	.905	.7645
45............	.8975	.770	27 49............	.910	.7775
50............	.887	.7725	30 22............	.899	.7775
55............	.8975	.7705	32 43............	.909	.776
60............	0.900	0.775	34 51............	0.9115	0.7755

the higher distillation point of sodium. Most of the attempts resulted in failures due to the formation of slight impure films on the metal next to the glass. These were probably oxide films,

as great care was always taken to clean the glass thoroughly. A mirror was, however, finally obtained which showed none of these films and appeared very perfect as viewed with the eye. The results are given in Table II.

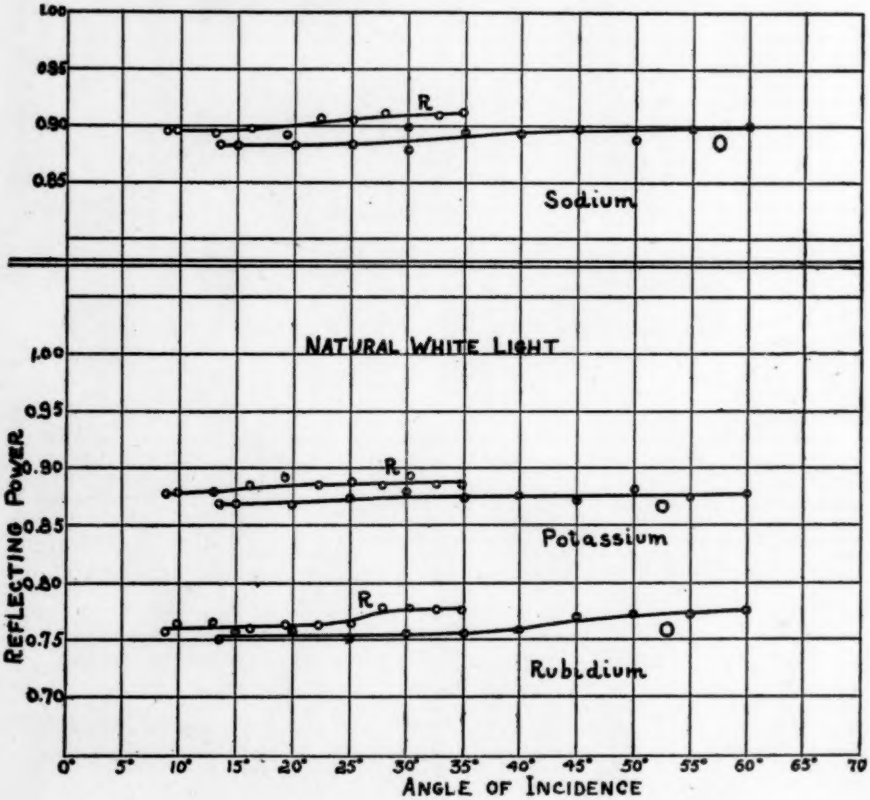


FIG. 8

No great difficulty was met with in the formation of rubidium mirrors, since the metal distills quite easily. The chief difficulty lies in obtaining the pure metal from its chloride. However, Rb is more easily oxidized than Na or K and hence a better vacuum must be insured. The values obtained with a mirror which showed no surface defects is given in Table II.

The values for Na are not plotted next to those for K in order to avoid confusion of contiguous points. In general, the reflecting

power rises slowly with the angle of incidence. The reflecting power is at first quite constant, then suffers a rather rapid rise, and then is nearly constant again. The values for the reflecting powers of the metals themselves are about 1 per cent higher than those for the whole mirror.

Na has the highest reflecting power, K being almost as good. Rb is less than K, so that the reflecting powers increase as the atomic weight decreases.

VIII. MONOCHROMATIC, POLARIZED LIGHT: ARRANGEMENTS OF APPARATUS

The source of light.—In this part of the work, it was proposed to investigate the reflecting powers of Na, K, and Rb for polarized

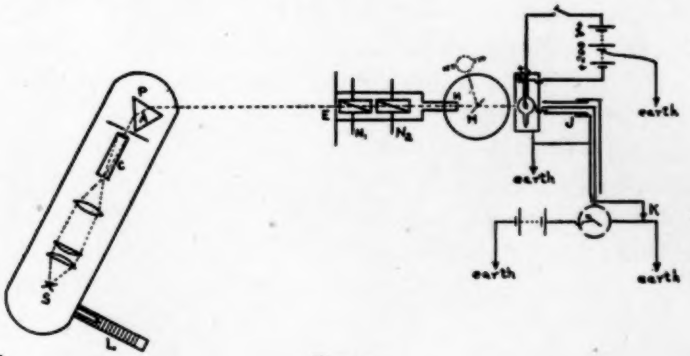


FIG. 9

monochromatic light. The arrangement of apparatus is shown in Fig. 9. In the case of white light, a Nernst glower was used as a source of light. Its use, however, was unsatisfactory, since it decreased so rapidly in efficiency owing to the polarization of the filament on direct current. The alternating current could not be used because it was too unsteady. Consequently for this part of the investigation, a 250-watt, nitrogen-filled, tungsten projection lamp was employed.

The optical system.—The light from one of the filaments *S* was focused upon the slit of the collimator *C*, after passing through the system of condensing lenses. The focal length of the collimator

was so adjusted that the emergent rays were just slightly convergent, the light being focused about 1.5 m away from the photo-electric cell. The central portion of the beam emerging from the collimating lens was allowed to pass through a good dispersing prism P, the spectrum being spread out over E. The source of light, condensing lenses, and prism were mounted on a movable table which could be rotated about an axis A through the center of the prism. Hence, by rotating this table any portion of the spectrum could be thrown upon the aperture E.

The light after passing through the rectangular nicols N_1 and N_2 and through the narrow slit H (7×1 mm), was incident directly upon the photo-electric cell, or else after reflection at the mirror M. The nicols served a double purpose, both for plane polarizing the light, and for calibration of the photo-electric current in terms of known light-intensities.

The photo-electric cell was used in connection with the spectrometer as in the previous work. The tube inclosing the nicols and containing the aperture H served to exclude extraneous light from the source. This tube was made purposely narrow toward the end in order to make the use of small angles of incidence possible when the photo-electric cell was swung around the spectrometer.

All light from extraneous sources was completely excluded by means of a double heavy cloth hung all around the apparatus, the room itself being partially darkened. That the screening was perfect was shown by the zero photo-electric current when the shutter of the cell was opened.

During observation upon the reflected light the nicols were arranged with their axes parallel to each other. The position of their planes of polarization was determined by the aid of a glass plate mounted so that the light was incident at the polarizing angle.

Calibration of apparatus in terms of wave-lengths.—The calibration of the scale L in terms of wave-lengths was effected by means of a Hilger wave-length spectrometer, the collimator of the instrument being placed in the position occupied by the photo-electric cell. It was found that the incident light was not purely monochromatic. A rapid test of the reflecting power of an alkali metal as a function of the wave-length showed this variation to

be very small. Hence it was unnecessary to procure purer monochromatic light.

The electrometer.—Since the light-intensities incident on the photo-electric cell are much smaller than in the case of white light, it was decided to use an electrometer to measure the photo-electric currents. The electrometer was of the Cambridge Scientific Co.'s type, giving a deflection of about 200 mm at a distance of 2.3 m for a difference of 1.5 volts between the two pairs of quadrants, there being 96 volts on the needle. The electrometer was placed in a fairly air-tight tin box which was well earthed to a water-pipe.

One pair of quadrants was always left earthed; the other pair (which could also be earthed) was connected to the cathode of the photo-electric cell. The latter connection was effected through a wire which was completely protected from outside disturbing influences by being run through a glass tube, the outside of which was wrapped in tin-foil and well earthed. This protection for the wire was found to be absolutely necessary. A loose joint J permitted the motion of the photo-electric cell about the spectrometer.

The needle of the electrometer was carefully insulated by means of amber, so that under ordinary working conditions no leakage could be observed when the quadrants were charged to a difference of potential. There was, however, a slow drift in the direction of an increasing deflection, which proved quite troublesome. This seemed to be clearly due to a "dark current" or a leakage current across the glass of the photo-electric cell, notwithstanding the presence of the earthed ring between anode and cathode. However, by putting this ring at a potential of about 200 volts below that of the anode, the drift was completely eliminated.

The voltage employed across the cell varied from 80 to 120 volts, the negative pole of the battery being earthed as shown in Fig. 9.

IX. METHOD OF OBSERVATION

The electrometer was used "ballistically," i.e., the photo-electric cell was exposed to the light for a definite short interval, and either the resulting steady deflection or the "first throw" of the needle noted. The time interval was given by a metronome

adjusted to beat (approximately) seconds. The shutter in front of the photo-electric cell could be operated by the observer at his observing-post at the telescope. At the beat of the ticker, the shutter could be "snapped up" and then smartly closed at the end of the chosen time-interval. Proper weighting of the cord insured the smooth working of the shutter, and, after some practice, the time-length of exposure could be made to a tenth of a second.

Toward the latter part of this investigation, the humidity of the spring air made it difficult for the electrometer to hold its charge, so that instead of waiting for the needle to come to rest and noting the steady deflection the observer noted the first throw of the needle. It was found that not only was the accuracy of observation not marred by this procedure, but that, furthermore, double the number of observations could be taken in a given time-interval.

Light of a known mean wave-length polarized either parallel or perpendicular to the plane of incidence was allowed to fall on the shutter of the photo-electric cell. The electrometer key was opened, and, when the needle had come to rest, the cell was exposed to the light for 10 or 15 seconds, and the steady deflection or else the first throw noted. The deflections for the reflected light were alternated with those for the unreflected beam as previously. Deflections varying from 50 to 200 mm were employed.

In order to calibrate the observed deflections in terms of known light-intensities, keeping conditions the same as before the nicol N_1 was rotated through various angles, observations were taken in adjacent quadrants and the mean taken to correct for any asymmetry of the nicols with respect to the axis of rotation. These mean deflections were then plotted against the squares of the cosines of the angles. The light-intensities corresponding to the observed deflections for the reflected light could then be read on the curve, giving the reflecting powers directly. A calibration-curve was thus obtained for every series of observations.

The true relation between the light-intensity and photo-electric current can be determined only under the imposition of proper experimental conditions. In the present investigation, the interest lay not so much in the relation between the current and the light-

intensity, as in the relation between the light-intensity and resulting electrometer deflections. Experimental conditions were always employed such as to give greater stability and accuracy to the observations. Consequently as low a voltage as possible was used on the needle. Also, in part of the work, as previously mentioned, the first throw of the needle was employed. For these reasons, it is not safe to assume that the photo-electric current is proportional to the electrometer deflections. Hence the curves between electrometer deflections and light-intensity are not to be assumed as being relations between photo-electric current and light-intensity. They are merely to be regarded as calibration-curves. In general the curves approximated to straight lines, being either slightly convex or concave to the illumination-axis, depending upon the experimental conditions imposed. No theoretical value is assigned to these curves, consequently they are omitted. It must be remembered, however, that the curves given under white light are true current-light-intensity curves.

X. OPTICAL PROPERTIES OF THE GLASS PLATES

In the case of white light it was shown that the reflecting power of the metal itself is only slightly different from that of the mirror as a whole, the former being only from a fraction to a little over 1 per cent greater than the latter.

It has been shown that within experimental errors, Fresnel's reflection equations hold for the front face of the glass. Hence the values for r were calculated from the equations

$$r=\frac{\sin^2(i-\theta)}{\sin^2(i+\theta)} \text{ and } r=\frac{\tan^2(i-\theta)}{\tan^2(i+\theta)}$$

for light polarized parallel and perpendicular to the plane of incidence, respectively.

The variation of r with the wave-length is rather small (0.2 per cent over the range employed), since the variation in index of refraction is small, the range of wave-lengths extending from about 450 to 650 $\mu\mu$. The values of r for yellow light are plotted in Fig. 10.

The range of wave-lengths used being in the visible portion of the spectrum, it could be assumed a priori that the transmission

power of the glass for the different colors would be the same as for white light, since no dispersion or color-effects are ever visible to the eye upon looking through the glass. Nevertheless it was decided to test out this point by a short method.

Light polarized perpendicular to the plane of incidence was incident on the glass plate at the polarizing angle. Very little

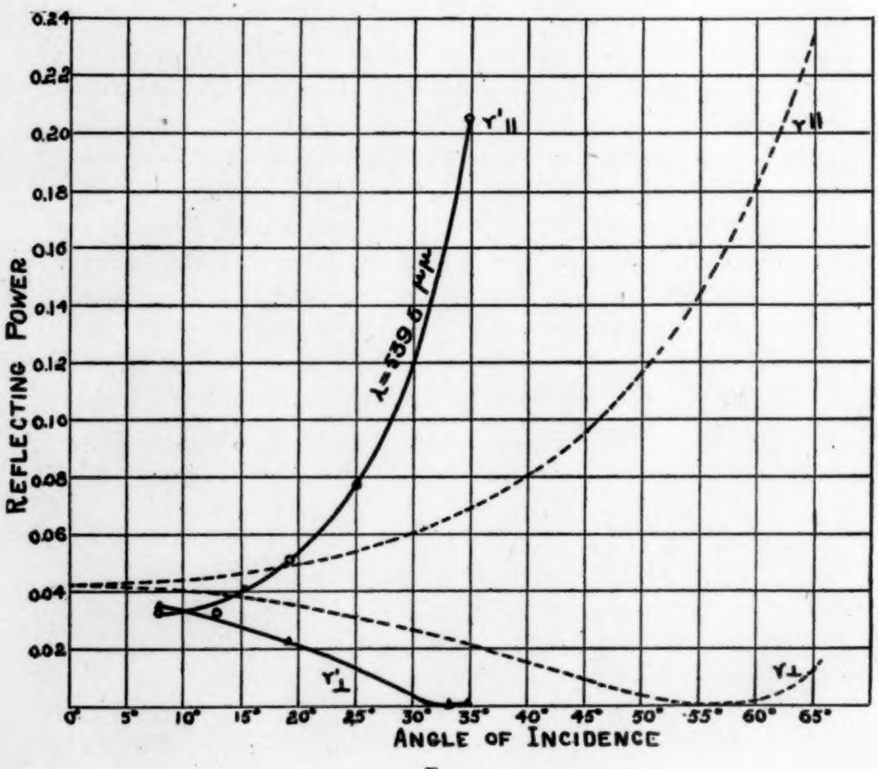


FIG. 10

light was thus reflected, practically all being transmitted. Hence the transmission power of the glass for that angle could be obtained by subtracting the transmitted from the incident light, allowing a small correction for the slight amount of reflected light.

Tests with various colors showed absence of any variation in the transmission power, the values for t being of the order given

in case of white light. As a result the values for t given in Fig. 7 were taken for this part of the work.

The values for r' (reflecting power of internal face of glass) for green light, taken for several angles of incidence, are shown in Fig. 10. These values for r' were used for all the colors. This use of r' is, however, not as radical as it might appear. In the first place, r varies very slowly with wave-length, hence the variation in r' must be likewise very small. Secondly, let us consider the equation for R in the form,

$$R=\frac{\frac{O}{I}-r}{t^2\left\{1-r'\left(1-\frac{O}{I}\right)-r\right\}}.$$

The values of $\frac{O}{I}$ vary from 0.8 to 0.95. $1-\frac{O}{I}$ is therefore a very small fraction, as well as r'. Consequently $r'\left(1-\frac{O}{I}\right)$ is very small compared to $1-r$, so that an error in r', even to the extreme extent of 5 per cent, could only result in an error of 0.1 or 0.2 per cent in the final value of R.

Inspection of the curves for r' shows that for small angles of incidence r' is less than r, but rises above r for angles of incidence approaching the critical angle at 41°. This rise is especially rapid in the case of light polarized parallel to the plane of incidence.

XI. RESULTS

The reflecting powers of potassium, sodium, and rubidium are given in the following tables and curves. The symbols $\parallel$ and $\perp$ on the curves indicate that the plane of polarization is parallel or perpendicular to the plane of incidence, respectively. In general, the reflecting powers are somewhat higher than those obtained for white, unpolarized light. The curves are similar to those obtained for a transparent medium, i.e., the reflecting power for light polarized parallel to the plane of incidence increases steadily with increased angle of incidence, while for light polarized perpendicular to the plane of incidence, the reflecting power decreases with increased angle of incidence. In the latter case the minimum value

reached would of course not be equal to zero as in the case, e.g., of glass.

The curves for K are not as smooth as those for Na and Rb owing to the fact that the steady deflection method was used in the case of K, while the method of first throw was used in the case of Na and Rb. Furthermore, nearly all of the points for Na and Rb are the mean of two values. Na has on the general average just

TABLE III

Reflecting Power (O) of Rb Mirror No. 2

Angle of Incidence	λ 640.9	λ 589.3	λ 539.6	λ 488.8	λ 454.6
Plane of Polarization Parallel to Plane of Incidence					
12°	0.852	0.821	0.826	0.812	0.804
20	.844	.820	.820	.815	.805
25	.828	.828	.825	.824	.805
30	.870	.829	.820	.837	.809
40	.873	.845	.860	.833	.823
50	.875	.849	.828	.864	.845
60	.872	.868	.863	.875	.865
65	0.888	0.868	0.868	0.872	0.860
Plane of Polarization Perpendicular to Plane of Incidence					
12°	0.808	0.777	0.790	0.802	0.759
20	.813	.794	.793	.776	.753
25	.792	.788	.788	.783	.764
30	.822	.775	.800	.773	.748
40	.785	.769	.782	.770	.739
50	.797	.765	.760	.769	.750
60	.787	.762	.793	.780	.766
65	0.790	0.761	0.775	0.783	0.756

a slightly better reflecting power than K, Rb being less than either as for white light.

To the author's knowledge, no other investigation on Rb has ever been carried out, so that comparison is impossible. Great faith is, however, placed in the curves for Rb, since the results obtained for green light for two different mirrors check very well with each other (see Tables IV and V). The results of Tables III and IV are shown in Fig. 11. In these tables λ is given in $\mu\mu$.

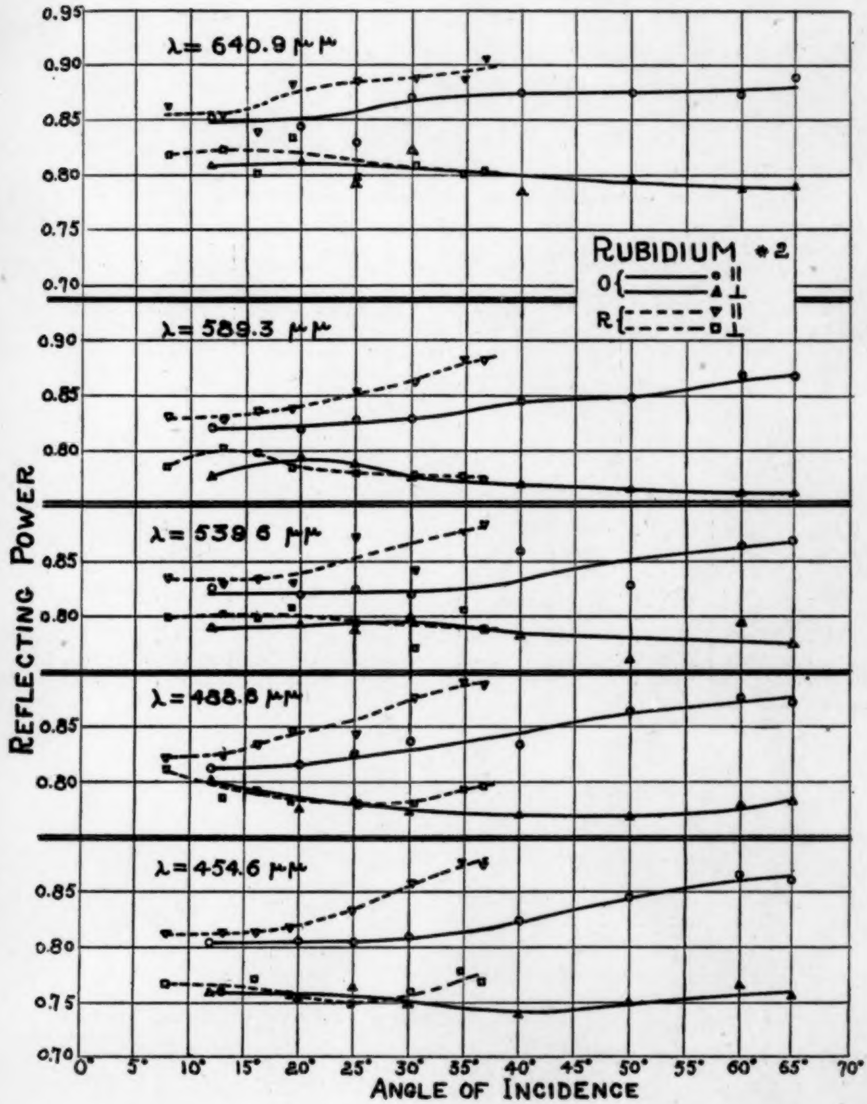

λ = 640.9 μμ
λ = 589.3 μμ
λ = 539.6 μμ
λ = 488.8 μμ
λ = 454.6 μμ
RUBIDIUM #2
O
R
REFLECTING POWER
ANGLE OF INCIDENCE
0.95
0.90
0.85
0.80
0.75
0.70
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
60°
65°
70°

FIG. 11

The results for Na and K are shown in Figs. 13 and 14.

The curves for Na for light polarized perpendicular to the plane of incidence are noteworthy. For small angles of incidence,

TABLE IV

REFLECTING POWER (R) OF RB NO. 2

Angle of Inc.	λ 640.9	Angle of Inc.	λ 589.3	Angle of Inc.	λ 539.6	Angle of Inc.	λ 488.8	Angle of Inc.	λ 454.6
PLANE OF POLARIZATION PARALLEL TO PLANE OF INCIDENCE									
7°54′...	0.862	7°53′..	0.831	7°53′..	0.835	7°52′..	0.821	7°50′..	0.812
13 4 ...	.854	13 3 ..	.829	13 2 ..	.830	13 0 ..	.824	12 58 ..	.813
16 13 ...	.838	16 12 ..	.837	16 10 ..	.835	16 8 ..	.834	16 5 ..	.813
19 18 ...	.881	19 16 ..	.838	19 14 ..	.831	19 11 ..	.847	19 8 ..	.818
25 8 ...	.885	25 6 ..	.855	25 3 ..	.872	25 0 ..	.843	24 56 ..	.833
30 25 ...	.888	30 22 ..	.863	30 18 ..	.841	30 14 ..	.875	30 9 ..	.857
34 55 ...	.887	34 51 ..	.883	34 47 ..	.877	34 42 ..	.891	34 36 ..	.878
36 48 ...	0.904	36 44 ..	0.882	36 39 ..	0.884	36 34 ..	0.888	36 27 ..	0.874
PLANE OF POLARIZATION PERPENDICULAR TO PLANE OF INCIDENCE									
7°54′...	0.818	7°53′..	0.785	7°53′..	0.799	7°52′..	0.811	7°50′..	0.766
13 4 ...	.823	13 3 ..	.803	13 2 ..	.802	13 0 ..	.785	12 58 ..	.760
16 13 ...	.802	16 12 ..	.798	16 10 ..	.798	16 8 ..	.792	16 5 ..	.771
19 18 ...	.833	19 16 ..	.785	19 14 ..	.810	19 11 ..	.783	19 8 ..	.756
25 8 ...	.797	25 6 ..	.780	25 3 ..	.793	25 0 ..	.780	24 56 ..	.748
30 25 ...	.809	30 22 ..	.778	30 18 ..	.771	30 14 ..	.780	30 9 ..	.760
34 55 ...	.801	34 51 ..	.776	34 47 ..	.805	34 42 ..	.794	34 36 ..	.778
36 48 ...	0.803	36 44 ..	0.773	36 39 ..	0.788	36 34 ..	0.796	36 27 ..	0.769

TABLE V

REFLECTING POWER FOR RB MIRROR NO. 1

FOR λ=539.6 μμ

PLANE OF POLARIZATION PARALLEL TO PLANE OF INCIDENCE				PLANE OF POLARIZATION PERPENDICULAR TO PLANE OF INCIDENCE			
O		*R*		*O*		*R*	
Angle of Incidence	λ 539.6	Angle of Incidence	λ 539.6	Angle of Incidence	λ 539.6	Angle of Incidence	λ 539.6
12°......	0.806	7°53′	0.814	12°......	0.805	7°53′	0.815
20.......	.828	13 2	.837	20.......	.802	13 2	.812
25.......	.837	16 10	.847	25.......	.813	16 10	.824
30.......	.838	19 14	.849	30.......	.808	19 14	.818
40.......	.843	25 3	.854	40.......	.801	25 3	.812
50.......	.850	30 18	.862	50.......	.789	30 18	.801
60.......	.863	34 47	.877	60.......	.795	34 47	.808
65.......	0.861	36 39	0.877	65.......	0.785	36 39	0.798

the reflecting power first increases and then decreases. This appears to become more marked as the wave-length decreases. This is the only evidence that has been obtained that may throw light on the selective photo-electric effect as depending upon the optical properties of the metals.

The Rb curves also show similar evidence, though not so marked as in Na.

The reflecting powers are given with reference to glass as the adjacent medium. Were the metals in contact with a vacuum, the results would have been slightly higher. The magnitude of

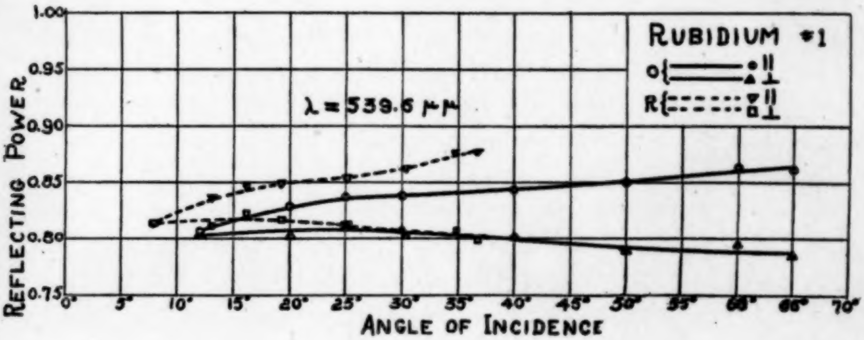


FIG. 12

this increase may be obtained as follows. Taking R. W. and R. C. Duncan's results for K for $\lambda = 589.3\ \mu\mu$, we have $n = 0.068$ and $\kappa = 22.1$. Hence, we obtain a value of 0.92 for the reflecting power of K by substituting in the formula for normal incidence, i.e.,

$$R = \frac{n^2(1+\kappa^2)+1-2n}{n^2(1+\kappa^2)+1+2n}.$$

It has been shown by Ingersoll[1] that the reflecting power of a metal in contact with a vacuum can be obtained from the reflecting power of the metal in contact with a medium of refractive index, m, by dividing n by m and substituting in the formula above for R. In our case, $m = 1.5155$, so that R would become in the case above, 0.914. The reflecting powers, as they are given in the

[1] *Physical Review*, **29**, 392, 1903.

tables and curves, would thus be a fraction of a percentage *higher* were the metal in contact with a vacuum instead of with glass.

XII. RELATION BETWEEN OPTICAL AND ELECTRICAL PROPERTIES OF METALS

Starting with Maxwell's electro-magnetic equations, it can be shown that, in the case of very good conductors like metals, the relation between the reflecting power, conductivity, and wave-length is given by

$$R = 1 - \frac{2}{\sqrt{\sigma c \lambda}} \tag{8}$$

where σ is the electrical conductivity in c.g.s. electro-magnetic units, c is the velocity of light, and λ is the wave-length. This relation holds theoretically only for very long wave-lengths. Hence, as the wave-length λ increases, the second term diminishes, and R increases, becoming unity for $\lambda = \infty$.

The variation of R for the alkali metals as a function of λ is shown in Fig. 15. There is a distinct rise of the reflecting power with increasing wave-length, thus confirming theory. The points on the curves represent the mean of the reflecting powers for light polarized parallel and perpendicular to the plane of incidence, and for an angle of incidence of 12°. The mean therefore represents very closely the reflecting power at normal incidence, to which the equation (8) applies.

In Table VI are given the experimental values for the reflecting powers for normal incidence. The values of the reflecting powers as given by equation (8) have also been calculated and inclosed in this table.

Inspection of Table VI shows that the experimental values of the reflecting power of sodium is about 3 per cent less than that calculated by R. W. and R. C. Duncan from their katopric measurements. On the other hand, the values of potassium in this table seem to be somewhat larger than those of Duncan.

In general the theoretical values are lower than the experimental, though the agreement in the case of Rb is very close. The reflecting power of Rb is thus confirmed by Maxwell's equation

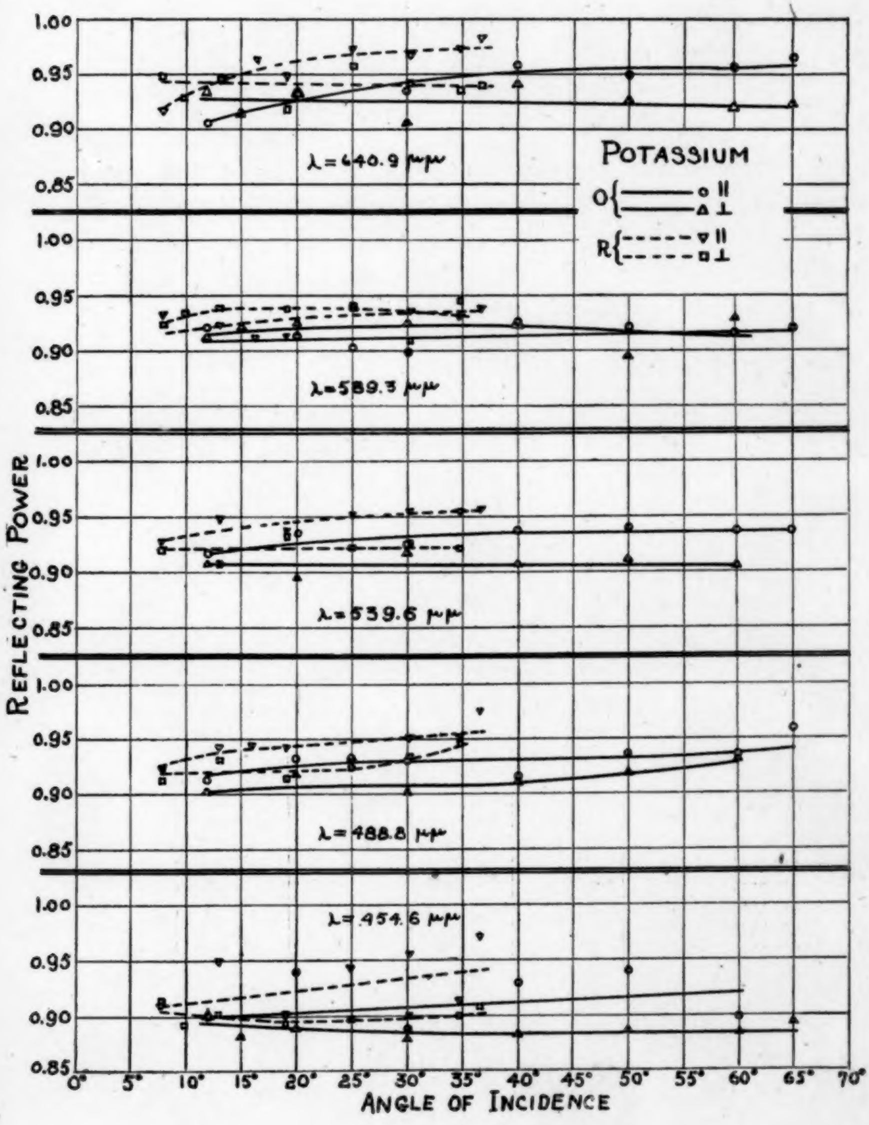

POTASSIUM
O
R
λ = 640.9 μμ
λ = 589.3 μμ
λ = 539.6 μμ
λ = 488.8 μμ
λ = 454.6 μμ
REFLECTING POWER
ANGLE OF INCIDENCE
1.00
0.95
0.90
0.85
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
60°
65°
70°

FIG. 13

of reflection. The discrepancy between theory and experiment becomes more marked if we put equation (8) in the form

$$\frac{(1-R)}{2}\sqrt{\sigma_{e.m.}}\,c=\frac{1}{\sqrt{\lambda}}. \tag{9}$$

The value of the expression on the left-hand side of the equation appears to be only a function of the wave-length, and hence ought to be independent of the metal used. Calculations for $\lambda=640.9\ \mu\mu$ made with Na, K, and Rb show, however, that the values of the left member of equation (9) are respectively 66.9, 69.3, and 117; while $\frac{1}{\sqrt{\lambda}}=124.4$.

This discrepancy between theory and experiment shows that Maxwell's equations do not hold for the visible spectrum. In view

TABLE VI

NORMAL INCIDENCE

$\sigma_{e.m.}$ for Na $=\frac{1}{5072}$ e.m.u. (21°7) } Hornbeck[1]
$\sigma_{e.m.}$ for K $=\frac{1}{7010}$ e.m.u. (20°7) } Hornbeck[1]

$\sigma_{e.m.}$ for Rb $=71\times10^{-6}$ e.m.u. (19°3) Guntz and Broniewski[2]

WAVE-LENGTH $\mu\mu$	NA		K		RB	
	Experimental	Theor.	Experimental	Theor.	Experimental	Theor.
640.9.......	0.945	0.897	0.933	0.879	0.840	0.829
589.3.......	.926	.893	.930	.874	.808	.822
539.6.......	.938	.888	.825	.968	.817	.814
488.8.......	.924	.882	.918	.861	.816	.804
454.6.......	0.914	0.878	0.912	0.857	0.789	0.797

of the modern electron theory this is not at all surprising, for Maxwell's theory does not take into account the effect of the resonating electrons within the metals upon the incident electromagnetic waves. That Maxwell's equation holds very well for

[1] *Physical Review* (2), 2, 217, 1913.

[2] C. R., 147, 1474, 1908; 148, 204, 1909.

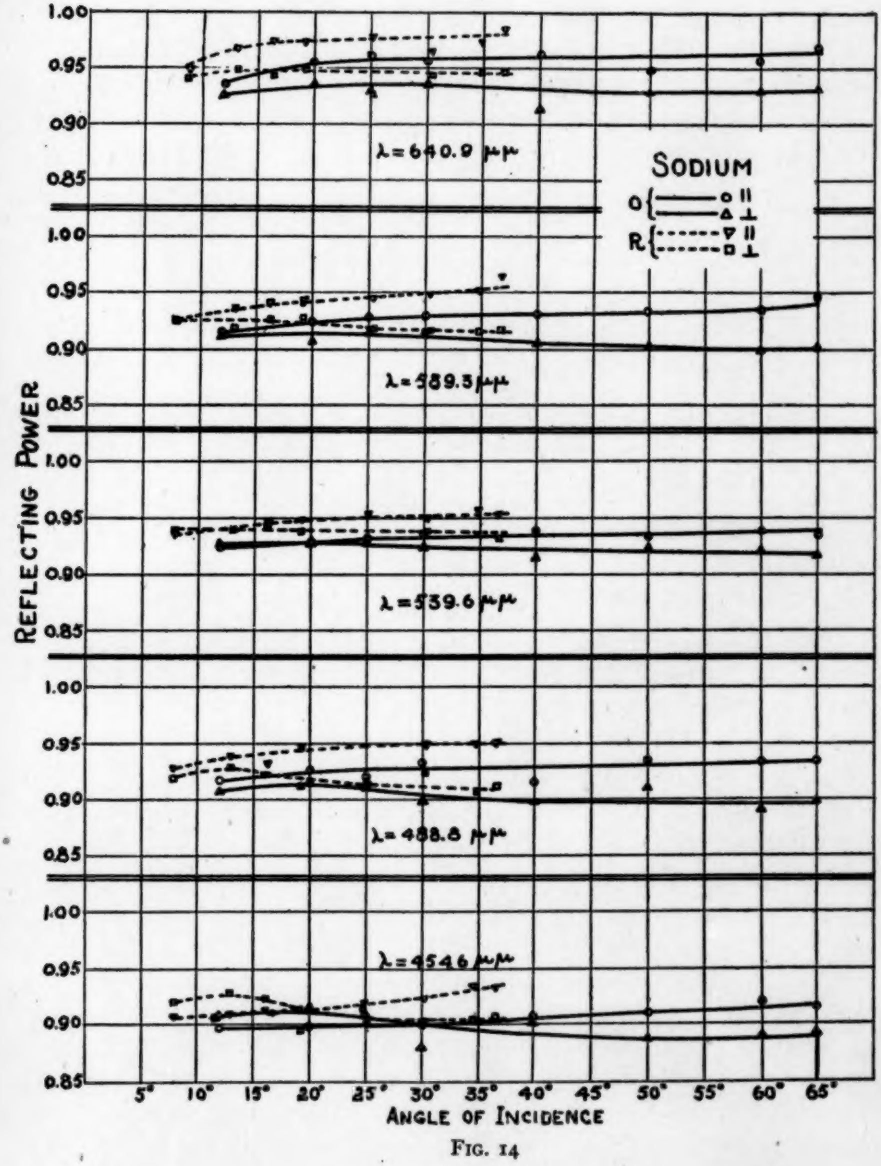

1.00
0.95
0.90
0.85
λ = 640.9 μμ
SODIUM
O
R
λ = 589.3 μμ
λ = 539.6 μμ
λ = 488.8 μμ
λ = 454.6 μμ
REFLECTING POWER
5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65°
ANGLE OF INCIDENCE

FIG. 14

large wave-lengths was shown by Hagen and Rubens[1] for wave-lengths ranging from 8 to 15 μ.

Inspection of Fig. 15, for the case where the angle of incidence is 35°, shows that the reflecting powers of the alkali metals for light polarized perpendicular to the plane of incidence are always less than the reflecting powers for light polarized parallel to the plane

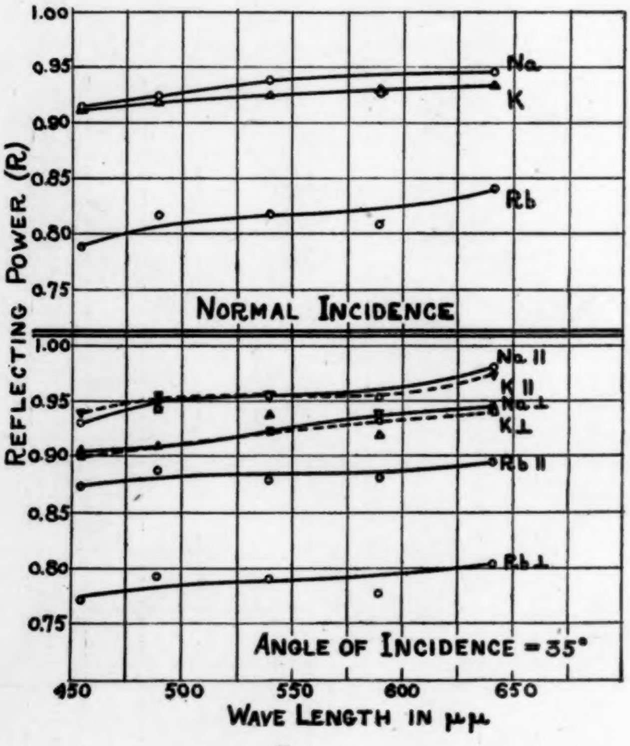


FIG. 15

of incidence. On the other hand, were the selective effect due to a change in the optical properties of the alkali metals, we should expect an abnormally high reflecting power for light polarized perpendicular to the plane of incidence. The range of wave-lengths employed in this investigation covers about one-half the

[1] *Annalen der Physik*, 11, 873, 1903.

selective region for potassium and about two-thirds that for rubidium. It therefore appears that the selective effect cannot be due to an abnormally high reflecting power in the region of the selective effect. This investigation must, however, be carried down to still smaller wave-lengths before the problem can be more definitely decided.

SUMMARY

1. The reflecting powers of sodium, potassium, and rubidium were determined for various angles of incidence, using white unpolarized light and also monochromatic light polarized parallel and perpendicular to the plane of incidence.

2. A rubidium-argon photo-electric cell was used as a photometer. It was calibrated in terms of known light-intensities by means of crossed nicols. The photo-electric current was found not to be strictly proportional to the light-intensity.

3. The alkali metals were used in the form of mirrors, which were made by distilling or pouring the metal on a glass plate forming a part of an evacuated cell.

4. Owing to reflection at the front and internal faces of the glass plate, the optical properties of the glass plate were determined in order to calculate the reflecting power of the metal itself. Fresnel's reflection equations for glass were verified.

5. The reflecting powers of Na, K, and Rb were found to decrease in the order named, i.e., as their atomic weights increased. The values for monochromatic light were found to be somewhat higher than those for white light. The results for Rb were found to be confirmed by Maxwell's equation for metallic reflection.

6. In the case of monochromatic polarized light, the reflecting power increased with increased angle of incidence for light polarized parallel to the plane of incidence, but decreased somewhat for light polarized perpendicular to the plane of incidence for the range of angles used.

7. The reflecting powers increased with increase of wave-length in accordance with Maxwell's theory.

8. The selective photo-electric effect does not seem to be due to any marked change in the reflecting powers of the alkali metals for light polarized perpendicular to the plane of incidence.

In conclusion, I wish to take this opportunity of expressing my thanks to Professor A. P. Carman for having so kindly placed the necessary facilities for research at my disposal, and to acknowledge my indebtedness to Professor Jakob Kunz for having suggested this problem, and for his many valuable and kind suggestions throughout this investigation.

Laboratory of Physics
University of Illinois
May 1916

THE STRUCTURE OF THE LITHIUM LINE λ 6708 AND ITS PROBABLE OCCURRENCE IN SUN-SPOT SPECTRA[1]

By ARTHUR S. KING

In connection with an investigation of the electric furnace spectrum of calcium, it became highly desirable to obtain definite evidence as to the origin of the line λ 6708 which usually appears in calcium spectra. It has been uncertain whether calcium could under certain conditions give a line of this wave-length, or whether the line is in all cases the well-known red line of lithium, which may appear as an impurity in other spectra. The question is important also in connection with sun-spot spectra, in which Hale and Adams[2] found a strong line of the wave-length specified. They also observed it much intensified in the outer regions of calcium and other arcs. The writer[3] found the line very strong in the furnace spectrum of calcium. If in these cases it is produced by calcium, the fact is important chiefly as an indicator of reduced temperature in sun-spots, but if the line is always due to lithium, it furnishes the clearest evidence we have of the presence of lithium in the sun. This latter view was taken by Hemsalech and De Watteville,[4] who in their study of the calcium flame spectrum considered that λ 6708 is due to lithium impurity and that it is the line occurring in sun-spots. Holtz,[5] however, in measuring the calcium arc spectrum according to the international standards, ascribed λ 6708 to calcium.[6]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 122.

[2] *Mt. Wilson Contr.*, No. 15; *Astrophysical Journal*, **25**, 75, 1907.

[3] *Mt. Wilson Contr.*, No. 35; *Astrophysical Journal*, **29**, 190, 1909.

[4] *Comptes Rendus*, **149**, 1369, 1909.

[5] *Zeitschrift für wissenschaftliche Photographie*, **12**, 101, 1913.

[6] After this manuscript was prepared, my attention was called to an article by H. G. Woodward (*Astrophysical Journal*, **41**, 169, 1915), in which the possibility of obtaining a calcium-arc spectrum free from the line λ 6708 is demonstrated in a very satisfactory manner. The portion of the present paper bearing on the origin of the line supplements that of Mr. Woodward with different evidence and reaches the same conclusion.

The relatively low dispersion used in the study of the calcium furnace spectrum showed λ 6708 as clearly double, though not resolved. It thus appeared possible that both calcium and lithium entered into the production of the line. Higher dispersion was then resorted to, the second order of the vertical plane grating spectrograph of 30-foot focus being employed, which gives a dispersion of approximately 1 mm = 0.89 A. A large number of spectrograms were then taken for a wide variety of conditions of the arc and furnace, the line being studied both with calcium and with lithium in the source. A satisfactory resolution of what proved to be a highly complex line was obtained in this way. Measurement of the components appearing under various conditions were referred to the calcium line λ 6717.940 (Rowland). When lithium was used in the arc or furnace, λ 6718 was put on the plate by means of the occulting device above the slit or by screening out the lithium line during the calcium exposure by a strip of paper passed in front of the plate.

RESULTS

When the source is such that λ 6708 might be due either to calcium or to lithium impurity, that is, with metallic calcium in the arc or furnace, or with clean carbons in the arc, a narrow doublet is usually obtained, of which the violet component is about twice as strong as the red. When lithium chloride was used in the source, a reversed line appeared which was photographed on numerous plates in juxtaposition to the narrow doublet; but it was evident that the reversed line could not have sharpened down to either component of the doublet without decided shift of its center. It thus appeared that the doublet occurring in the calcium spectrum is distinct from the lithium reversed line and might belong to calcium. However, a very similar doublet was obtained by Zeeman[1] in absorption when white light was passed through an exhausted vessel containing lithium vapor, the relative intensity of the components being the same in the two cases, while the interval of 0.144 A measured by Zeeman is in fair agreement with the mean value of 0.152 A

[1] *Proceedings of the Amsterdam Academy*, **15** (II), 1130, 1913; **16** (I), 155, 1913.

obtained from six arc and furnace photographs. Kent[1] observed the same doublet in emission from a vacuum tube containing lithium, and measured the separation as 0.151 A. This close agreement, together with other observations to be described, indicates that the doublet is in no case due to calcium.

A remarkable condition became evident when the quantity of lithium in the arc was such as to give a rather narrowly reversed line. A bright line then appeared inside of the reversal and slightly to the red of its center. Visual observations showed the same appearance as that recorded on the plates. As the quantity of lithium in the arc was increased, the bright line was gradually suppressed by the absorption of the vapor producing the reversal of the main line. Turning the spectrograph so as to bring the axis of the arc-image parallel to the slit showed the emission line weakening toward the upper pole, where the denser absorbing vapor appeared as a red hood beneath the arc terminal.

Further experiments were then made with a very small quantity of lithium in the arc, a drop of dilute solution of the chloride being placed on either carbon or copper poles. By projecting the image on a long slit, the spectrum line was made to register the condition in the arc from pole to pole. Near the upper terminal and extending to the middle of the arc, the line consisted of an unsymmetrical triplet. The bright line usually appearing within the reversal was present as the middle component, while the sides of the reversal had become two sharp lines, sometimes with incipient wings. The red component of the triplet had a close satellite on its red side. The triplet blurred in the middle of the arc, and from here to the lower (positive) pole appeared a gradual development of the two components of the close doublet which it had been thought might belong to calcium. Putting the calcium line λ 6718 on the plate by a second exposure to serve as a standard, it was found that the doublet in the lithium arc agreed closely as to wave-length, separation, and relative intensity of components with the doublet given by calcium in the arc or furnace. Unless it was added by separate exposure, the photographs showed no trace of the calcium line λ 6718, which is good evidence that the doublet was not due to

[1] *Astrophysical Journal*, 40, 337, 1914.

calcium mixed with the lithium, since in the calcium arc λ 6718 is much stronger than λ 6708.

The components of the lithium triplet were studied to best advantage in the furnace spectrum, especially with regard to the separation of the side components. In the vacuum furnace, with a small quantity of lithium vapor present, the components of the triplet were sharp, with quite the appearance of Zeeman components, the phenomenon being clearly distinct from the regular reversal effect.

Measurement of a number of photographs proved that the interval between the side components was decidedly variable, this seeming to be controlled by the amount of vapor present. Nine furnace photographs gave intervals ranging from 0.25 A to 0.36 A, a difference much greater than the error of measurement for components as sharp as these. As the separation became wider, the middle component became weaker and the satellite by the red component strengthened. With a larger quantity of vapor, the side components lost their sharpness and gave the regular reversed line with widely shaded wings. A description of a succession of furnace runs at about 2100° C. without fresh supply of lithium will serve to illustrate the changes and the transition to the doublet stage. Starting with a small supply of vapor, the components came closer together on successive plates with a strengthening of the central line until the three were no longer resolved. The next photograph showed the doublet with the usual separation of components. The interval of this doublet seems to be constant, as the measurements on good plates have never differed by more than 0.007 A.

The variation of the lithium components is thus shown to be the same in arc and furnace, and the controlling agency in each has seemed to be the amount of vapor in the source. The appearance of the two sets of components in the arc near the positive and negative poles respectively can scarcely be dependent upon the discharge conditions, since either set can be produced in the furnace without material temperature change. The whole effect agrees with the observations of Nutting,[1] who studied line structure for a number of elements by means of the echelon spectroscope. He

[1] *Astrophysical Journal*, 23, 64, 1906.

observed only a broadening of the red lithium line, but in other spectra frequently recorded a "twinning" of sharp components which spread apart with increasing material in the arc and changed into the winged structure of regular reversal. In some cases a central component was present, as is the case for the lithium line. The variable interval of the components suggests electrical resolution, and Stark[1] has recently developed a theory of the connection between electrical resolution and the widening of spectrum lines. The production of the effects in the furnace shows that they are not due to an external electric field, but it would seem that there are strong possibilities in the action of interatomic fields, in the variation of which the vapor-density might well be the controlling agency.

An observation of the structure of λ 6708 by Jewell in an early paper by Rowland[2] is explained by the foregoing results. Jewell notes: "With but little material in the arc this is a difficult triplet. The violet component is very strong, the red component about half as strong, and between them but nearer the red component is a very narrow line much weaker than either of the others." This appearance would result from the use of a concave grating and the projection of most of the length of the arc on the slit. The strong violet component of the doublet would then blend with the violet component of the triplet, producing an unsymmetrical triplet of which the central and red components seen by Jewell correspond with those on my photographs.

In Table I, are given measurements of those members of the group at λ 6708 whose wave-lengths seem to be invariable. The mean wave-length of the variable side components of the triplet appears to be that of the center of the reversed line into which they gradually develop. The measurements were made in arc spectra from the sharp calcium line λ 6717.940 (Rowland), the wave-length of which in the international system is given by Holtz as 6717.70.

The mean wave-length of the close doublet in the international system is 6707.81, which agrees exactly with the value given by

[1] *Jahrbuch der Radioaktivität und Elektronik*, 12, 349, 1915.

[2] *Astronomy and Astrophysics*, 12, 344, 1893.

Holtz, who measured it as an unresolved line ascribed to calcium. This mean wave-length of the doublet agrees closely with the wave-length of the reversed line; but the agreement would cease if the doublet were faint, as when produced by a small impurity, so that the measured wave-length would be that of the strong violet component. A discrepancy as large as 0.07 A might thus result. The possibility of variable wave-lengths due to complex structure has been recognized by other observers, and we may have here the key to the condition which Burns[1] notes: that "lines of impurities are not as yet recommended for standards," since a small impurity may give a distinct set of components.

TABLE I

WAVE-LENGTHS OF COMPONENTS OF λ 6708

	No. Plates	λ (Rowland)	λ (I. A.)
Violet component of doublet	7	6707.977	6707.74
Red component of doublet	3	6708.125	6707.88
Center of reversed line	8	6708.053	6707.81
Bright line inside of reversal	6	6708.072	6707.83

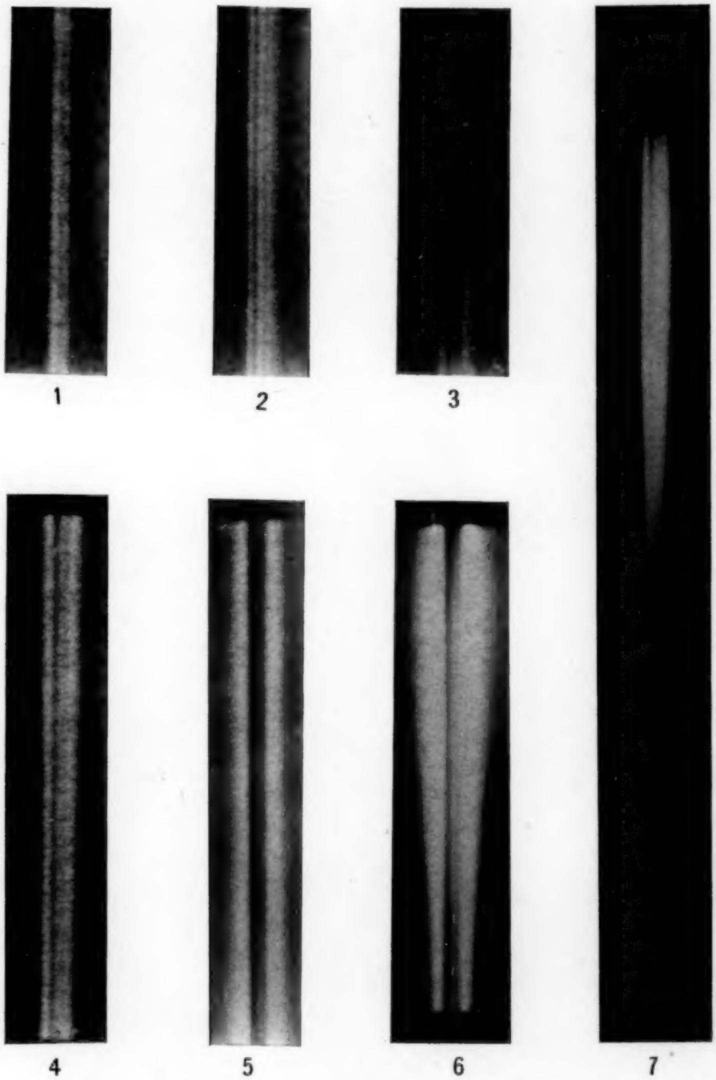
Various conditions of the lithium components are shown in Plate IV. The first three enlargements are of the narrow doublet and two states of the triplet in the furnace, the strength of the red satellite in No. 3 giving a quadruple structure. The next three are for the arc with increasing quantities of vapor, the side components being almost sharp in No. 4, while Nos. 5 and 6 show the regular reversal with the bright line inside. No. 6 was taken with the arc-image parallel to the slit, showing the extinction of the bright line near the upper terminal. No. 7 shows the simultaneous production of both sets of components, the one near the positive, the other near the negative pole.

COMPARISON WITH λ 6708 IN THE SUN-SPOT SPECTRUM

Sun-spot spectra showing λ 6708 have been photographed by Mr. Ellerman and Mr. Nicholson, using the first and second orders of the 75-foot spectrograph on Mount Wilson, and kindly placed at

[1] *Bulletin of the Bureau of Standards*, **12**, 179, 1915.

PLATE IV



λ 6708 in Furnace and Arc Spectra

1. Doublet appearing in furnace or arc with trace of lithium vapor.
2. Triplet which takes the place of the doublet when slightly more vapor is present.
3. Appearance of line in furnace with more vapor than for No. 2.
4. Triplet in arc, with side components beginning to show the widening characteristic of reversal.
5. Reversed line in arc with inner component still visible.
6. Reversed line in arc showing fading of inner component near upper electrode where absorption is strongest.
7. Combination of triplet and doublet in arc when vapor density gradually increases from lower to upper terminal.

my disposal for comparison with the laboratory plates. The line seems to be absent from the regular solar spectrum, the faint line in Rowland at λ 6708.176 apparently being too far to the red. In the spot spectrum, the line is rather wide and of low density, so that the first-order plates, with a scale of 1 mm=0.713 A, proved much better for measurement. The mean value from four plates is λ 6708.065. Considering the character of the line, which, exclusive of wings, is about 0.2 A wide, this is in fair agreement with λ 6708.053 for the reversed lithium line and is very close to the mean value, λ 6708.062, of the center of this line and of the bright line appearing within the reversal. Such dissymmetry as is present in the sun-spot line is toward the red, so that the condition of the vapor is probably not that giving the close doublet with a strong violet component. Second-order plates taken with nicol prism and quarter-wave plate show a decided Zeeman effect for the sun-spot line. This, together with the strength of the line, makes it probable that λ 6708 is not one of the fluting lines which are plentiful in this region, though possibly it may be blended with such a line.

The material here presented appears to furnish a strong probability that the sun-spot line is due to lithium, and we have the remarkable condition that an element of very wide distribution in terrestrial substances is apparently unable to show its spectrum in the solar atmosphere except over sun-spots.

The relative intensities of λ 6708 and the strong orange line λ 6104 were compared in a set of furnace spectra of lithium at various temperatures. At 1650° C., λ 6708 was very strong and reversed, while λ 6104 was barely visible. Above 2000°, the latter line gained in relative intensity, though still much weaker than λ 6708. This behavior of λ 6708 justifies its use as a criterion of low temperature. λ 6104, if present in the spot spectrum, is extremely faint. Other lithium lines will be searched for when spot photographs of the more refrangible region are available, but if they are not found their absence may be fairly ascribed to a low-temperature condition, since λ 6708 is by far the most sensitive to a weak excitation in laboratory sources.

SUMMARY

1. The complex lithium line λ 6708 may appear under different conditions with two distinct sets of components, either as an unsymmetrical doublet or as a triplet of variable separation.

2. In a third stage, the side components of the triplet change into the ordinary reversal, within which the central component still can be seen.

3. All three conditions of the line may be produced in either arc or furnace, the doublet and triplet sometimes appearing at the same time in different parts of the arc.

4. The observations show that the line at λ 6708, often found in calcium and other spectra, has the same structure and wave-length of components as the lithium line when produced by a source containing but little of the substance. The line is probably always due to lithium, and if low-temperature conditions are present in the source, may attain a very high relative intensity.

5. Measurements of the strong sun-spot line λ 6708, which is probably absent from the photosphere, agree so closely with the wave-length of the arc and furnace line as to leave little question regarding the presence of lithium in the solar atmosphere; while the high intensity of the line at low furnace temperatures is evidence of the correspondingly low temperature of sun-spots.

MOUNT WILSON SOLAR OBSERVATORY
July 7, 1916

THE EFFECT OF HAZE ON SPECTROSCOPIC MEASURES OF THE SOLAR ROTATION

By RALPH E. De LURY

Spectroscopic determinations of the rate of the sun's rotation by different observers at various times present remarkable and puzzling differences. Certain sources of error have been proved to be present; but other explanations of some of the differences are of a hypothetical nature and are veiled in doubt. It is the object of this note to present with supporting evidence a new interpretation which seems to clear up much of the uncertainty attached to the problem of the solar rotation.

DIFFERENCES IN MEASURES OF SOLAR ROTATION

Notable observed differences are:

(1) *The measurements of the solar rotation made by different observers exhibit a large range of values.*—For example, the values of the equatorial solar velocity, derived from about twenty groups of determinations, range from 2.11 to 1.86 km per sec. Furthermore, *measurements by the same observer of a series of plates taken over a short interval of time frequently show a considerable range in their values.*

(2) *Some observers have found a difference in velocity for different spectral lines, while others have not.*—The determinations by Adams and Miss Lasby at Mount Wilson in 1906–1908 show such differences,[1] and this is confirmed[2] in 1915 by St. John, Adams, and Miss Ware, and also in Ottawa by the writer in 1915, a summary of these measurements being given later in this paper. On the other hand, all other observers (the writer included) find no serious difference for different lines in the interval 1909–1913. Hence

[1] Adams, *Mt. Wilson Contr.*, Nos. 20, 24, 29; *Astrophysical Journal*, **26**, 203, 1907; **27**, 213, 1908; **29**, 110, 1909; Adams and Lasby, *Publication No. 38, Carnegie Institution of Washington.*

[2] St. John, Adams, and Ware, *Popular Astronomy*, **23**, 641, 1915.

the conclusion: *The difference in velocity for different spectral lines is a variable, being present in some observations and apparently absent from others.*

(3) *One observer found that the northern and southern hemispheres of the sun rotated at different rates.*—The observations of Hubrecht at Cambridge[1] alone give information on this point. In 1911 the writer suggested the method of using simultaneous exposures from the center of the solar disk and from the limbs for determining the rates of rotation in the two hemispheres independently,[2] and since the apparatus was received in 1913 he has been making such observations; in 1915 a similar method was started at Mount Wilson,[3] so that more evidence on this point will soon be at hand.

(4) *Some observations show a value of the rate of rotation progressively increasing with wave-length over the small range of wave-lengths covered by a plate; a great many more observations do not exhibit this effect.*—The 1906–1907 series[4] of Mount Wilson measurements show this effect, while the 1908 series[5] does not. Some measurements by Schlesinger in 1909, and those by Hubrecht[6] in 1911 show the effect. All other observations appear to be free from this effect.

MECHANICAL EXPLANATION OF DIFFERENCES

The following explanations of the foregoing results have been or may be offered:

(*a*) *Instrumental errors.*—Such instrumental errors as would be caused by uneven illumination of the prism or grating, combined with observations of the spectrum out of focus, may account for part of results (1), (3), and (4).

(*b*) *Observational errors.*—Small inaccuracies in determining the points observed are possible, but it is unlikely that these could ever equal 0.5 per cent.

[1] Hubrecht, *Monthly Notices*, 73, 5, 1912.

[2] De Lury, *Report of the Chief Astronomer, Ottawa*, 1911, p. 290.

[3] St. John, Adams, and Ware, *loc. cit.*

[4] See footnote 1, p. 177.

[5] *Ibid.*

[6] Hubrecht, *loc. cit.*

(*c*) *Errors of measurement.*—In 1910 the writer suggested that errors of measurement might account for (1) and (2). He tested this explanation of (2) by mechanically introducing displacements of the spectral lines the same for all lines and of configurations and magnitudes of displacement similar to actual observations; a slight tendency to systematic difference for different lines was found in a series of twelve of these "imitation" rotation plates, as well as a systematic difference depending on the direction of the plate.[1] These plates were taken in the region of λ 4250, where Adams and Miss Lasby found the differences for different lines,[2] and the plates were sent to them in the hope that their measures of the same lines mechanically shifted would settle the question as to whether the differences for different lines in their original measurements were due to personal errors. Unfortunately they did not have time for the measurements, hence the part played by systematic error of measurement in their 1906–1908 determinations remained unsettled. This explanation of (1) was tested by having various observers measure the same lines on the same plates. J. S. Plaskett kindly offered to co-operate with the writer in measuring the above-mentioned twelve plates of the mechanical shifts, with the result that a systematic difference between the two measures of about 2 per cent was discovered. This difference persisted throughout the measurements of the solar rotation in 1910–1913. These suggestions of the writer followed by the comparative measurements led to these recommendations made at the meeting of the International Solar Union held at Bonn, in 1913: "It is highly desirable to trace to their source the systematic differences that are found in the values of the solar rotation by different observers. . . . . Investigation should also be made into the personal differences that are found in measures of the same plates by different observers." (In this connection it would seem advisable to have a series of plates, say one or two from each observer, measured by the automicrophotometer at Mount Wilson, and then passed around among the various observers for measurement.)

[1] De Lury, *op. cit.*, p. 264; *Journal of the Royal Astronomical Society of Canada*, **5**, 384, 1911.

[2] See footnote 1, p. 177.

PHYSICAL EXPLANATIONS OF DIFFERENCES

The foregoing explanations are based upon the possibility of instrumental, observational, or personal errors; those which follow are based on physical considerations:

(*d*) *Convection in the solar atmosphere.*—Local convection currents undoubtedly account for some of the differences obtained by the same observer under apparently similar conditions (1), and it is quite possible that in small series of observations the mean may be considerably distorted by this cause. Adams found instances of such local motions in the neighborhood of spots.[1] The writer found in one case a difference of 8 per cent between the top and bottom of a spectrum 1 mm wide, the lines being quite visibly bent from their normal straightness.

(*e*) *Periodic variation in the rate of the solar rotation.*—From variations in the visual measurements of Dunér (at Upsala, 1887–1889 and 1899–1901) and of Halm (Edinburgh, 1901–1906), the latter suggested that there was a periodic change in the sun's rate of rotation. If such is the case (1) could be accounted for, partially at least; and since there is periodicity in sun-spots and asymmetry in the spottedness of the northern and southern hemispheres, (3) might result from such periodic variation; and possibly result (2) could be explained by such periodicity, for the evidence on this point seems to bear some relation to the sun-spot variation.

(*f*) *Variation in the angular rate of rotation depending on level in the solar atmosphere.*—When Adams discovered differences in angular velocity for different lines of the spectrum (2), he suggested[2] that it was due to the fact that the gases producing the different lines existed at different levels (an assumption apparently supported by other lines of evidence) and that the angular rate of rotation increased with elevation. To account for the additional facts mentioned in (2) above, this explanation would have to be modified by adding: *and such variation in the angular rate of rotation varies periodically.*

[1] See footnote, 1, p. 177.

[2] *Ibid.*

(*g*) *Sky spectrum.*—Halm noted the possibility of error caused by the sky spectrum blending with the displaced spectrum of the limb, and observers have for the most part been careful to select the clearest days for observation. However, there seems to be error due to this source in some of the observations. The writer made, in 1911, some tests of the effect of sky spectrum in lessening the rotation displacement, with the result that for the very clearest days there seemed to be little error from this source.[1] This work led to the consideration of the general question of blended spectra, and in 1912 measurements of blends of spectra of limb and center were made which showed a striking, though predicted, relationship between measured displacements and line-intensity, owing to the fact that the difference in intensity for a line at limb and at center increases in general with decrease in intensity of the line.[2] These results led to the following explanation (*h*), though mentioned previously, presented only now because recent results in the measurement of the solar rotation at Ottawa by the writer, and at Mount Wilson[3] by St. John, Adams, and Miss Ware are strikingly well explained by it.

(*h*) *Spectrum of haze.*—It has been shown[4] (see also later) that a variable haze, between the observer and the sun, causing to be blended on the spectrum of the limb a spectrum of variable intensity and of character somewhat similar to that of the center of the solar disk in regard to intensity and wave-length of the spectral lines, causes: (i) the spectroscopic determinations of the solar rotation to vary, and (ii) the velocities of rotation from the different lines to decrease in general with decrease in intensity of the lines, the amount of the decrease in velocity for a given line depending on the strength of the continuous spectrum due to the haze relative to the continuous spectrum of the limb and on the ratio of the intensities of the line in the spectrum of the haze and in the spectrum of the limb. Observations already made make it seem probable that the variable terrestrial atmosphere and its

[1] De Lury, *Report of the Chief Astronomer, Ottawa*, 1911, p. 281.

[2] De Lury, *Journal of the Royal Astronomical Society of Canada*, 10, 201, 1916.

[3] St. John, Adams, and Ware, *loc. cit.*

[4] See footnote 2.

clouds and hazes are sufficient to account for differences (1) and (2), after eliminating the systematic and accidental errors mentioned above. But if in any series of observations the spectrum of terrestrial haze can be proved of insufficient strength, then we may introduce the idea of haze existing between the earth and the sun, near the sun, or even in the solar atmosphere (such as produced by matter falling in variable amounts into the sun and requiring an interval of time before being swept along in the general rotation). Such a variable haze possibly could account for the differences in the solar radiation observed by Abbot and others; it would be interesting to make simultaneous observations of solar rotation and radiation to see whether the changes in their values synchronize.

That explanation (*h*) is the true explanation of the residual differences in (1) and (2) above, after due allowance has been made for the other known sources of error, seems established from the similarity of the following three series of results, dealing with measurements of blended spectra, measurements of the solar rotation at Ottawa on plates made through different amounts of haze, and measurements of the solar rotation made at Mount Wilson.

MEASUREMENTS OF BLENDED SPECTRA

In the paper cited, it has been shown that the measured rotational displacements of the lines from the limb when blended with the lines—undisplaced by rotation—from the center of the solar disk decrease progressively with decrease in the intensity of the lines; and this was explained as due to the fact that the difference in intensity between lines in the spectra of center and limb decreases, in general, with increase in intensity of the lines. There are exceptions to this latter generalization which serve to test the various theories (see later). The accompanying summary (Table I) of the first table in the paper quoted will suffice to illustrate the general results. It is thus seen that the lessening of the displacement due to rotation in the blend with the spectrum of the center is greater progressively with decrease in intensity of the line, which, in turn, is accompanied by steadily increasing values

of the ratio of intensity from center to limb, and decreasing values of the ratio of width at center to limb. (Thus decreasing intensity at the limb seems to be accompanied by increasing width. To explain this the writer has advanced the hypothesis that the

TABLE I

BLENDED SPECTRA, λ 5600

Mean displacements of equatorial limb lines blended with five different blends with center spectrum in which the ratios of the densities of deposit on the photographic plate from the continuous spectrum of the limb to the total of continuous spectrum were 0.89, 0.83, 0.74, 0.62 and 0.54; mean ratio, 0.72.

Plate, L854, September 20, 1911

Line-intensity, center...	1	2	3	4	5	6	8
Line-intensity, limb....	0	1−	2	3	5−	6−	7
Line-width, center.....	4.8	4.2	5.4	6.8	7.8	7.2	9.2 km per sec.
Line-width, limb.......	6.2	5.6	5.8	6.6	8.2	8.0	8.6 " "
No. of lines...........	3	6	5	2	1	1	1
Mean velocity from blends.............	1.553	1.573	1.575	1.594	1.633	1.648	1.651 " "
Equatorial velocity not blended............	2.026	2.053	2.014	2.053	2.085	2.085	1.978 " "
Mean............							2.042

widening and weakening of the lines at the limb are due to convections similar to those in the penumbral regions of spots. Other factors come in to play and account for many exceptions. The question will be discussed soon in another communication.)

MEASUREMENTS OF THE SOLAR ROTATION AT OTTAWA ON HAZY DAYS

The results from the measurements of the solar rotation on hazy days for varying degrees of haze show a striking similarity to those from the measures of the artificial blends as shown in Tables II, III, and IV. It will be thus seen that the differences of percentage between the values for intensity 1 and 22 are: Table II, 1.2; Table III, 4.6; Table IV, 8.2. After the observations of Table IV were made, a photographic comparison of the intensity of the spectrum of the haze relatively to the spectrum of the limb was secured; however, the haze was continually varying so that only a rough approximation could be arrived at, and from this it would seem that the average ratio of intensity of the continuous

spectrum of the haze to the continuous spectrum of limb and haze for the observations of Table IV was 12± per cent. This would involve the assumption that the haze in Table II was about 2 per cent, while the haze for observations of Table III was about 7 per

TABLE II

SOLAR ROTATION, λ 5200

March 11, 1:30 P.M., 1916, very slightly hazy, 6 *double* observations, i.e., 2 strips of spectrum from each limb

	Mean	Mean	Mean	Mean	Mean
Intensity	1	2	5.3	22	5.3
Number of lines	3	11	7	3	24
Equatorial velocity	1.956	1.972	1.972	1.968	1.967

TABLE III

SOLAR ROTATION, λ 5200

June 16, 4:15 P.M., 1915, slightly hazy, 6 double observations

	Mean	Mean	Mean	Mean	Mean
Intensity	1	2	5.3	22	5.3
Number of lines	3	11	7	3	24
Equatorial velocity	1.808	1.842	1.845	1.883	1.843

TABLE IV

SOLAR ROTATION, λ 5200

March 3, 12:55 P.M., 1916, very hazy, haze varying, 3 double observations

	Mean	Mean	Mean	Mean	Mean
Intensity	1	2	5.3	22	5.3
Number of lines	3	11	7	3	24
Equatorial velocity	1.738	1.760	1.814	1.887	1.816

cent. These are of course only rough estimates, but they serve to point out the necessity of very accurate measures of the relative strengths of the spectrum of the haze and the spectrum of the limb. When such are made and accurately correlated with measurements of solar rotation for groups of lines of different intensities, it will be possible to eliminate the effect of the spectrum of the haze from any similar series of measurements of rotation. Such being the

case, it should be possible to estimate the strength of haze present during the Mount Wilson observations.[1]

MEASUREMENTS OF THE SOLAR ROTATION AT MOUNT WILSON

TABLE V

SOLAR ROTATION, λ 5200

1914–1915 measurements (St. John, Adams, and Ware, *Popular Astronomy*, **23**, 641, 1915)

	Mean	Mean	Mean	Mean	Mean
Intensity	1	2	4.9	22	6.4
Number of lines	2	5	9	3	19
Equatorial velocity	1.924	1.933	1.945	2.043	1.950

It is seen from Table V that the difference between the values for lines of intensity 1 and 22 is 6.1 per cent. It would seem that, if this is altogether ascribable to haze, there was an overlapping spectrum of the haze of about 9± per cent in these observations. The three lines of average intensity 22 were the same as in the Ottawa observations, namely, the three strong Mg lines in the *b* group, λ 5167 to λ 5184, but the lines of intensity 1 could easily yield different results in the two series, 3 in the Ottawa observations and 2 in the Mount Wilson observations. However, it seems likely that there must have been a considerable effect of haze during the latter observations. The large difference between the values of the rotation in the two series is probably accounted for by some of the other sources of error, though the Ottawa values in Table II (very slight haze) are nearly the same in the mean, the strongest lines being, however, exceptionally high in the Mount Wilson measures. That is a question which can best be attacked after the influence of the spectrum of light scattered from haze or optical parts has been accurately eliminated.

MEASUREMENTS TO TEST THE LEVEL HYPOTHESIS

The measurements of the solar rotation given in Tables VI and VII seem to support the haze explanation and to disprove the level hypothesis, unless the latter be assumed to be variable, as pointed out above.

[1] St. John, Adams, and Ware, *loc. cit.*

In Table VI are given the measurements of 6 lines of intensities 0 and 1 paired off with 6 lines of intensities 4–15, giving a great difference in penumbral displacements in spots, interpreted as

TABLE VI

SOLAR ROTATION, λ 4500

Ottawa, June 30–July 25, 1910, 32 observations

	Mean	Mean	Mean
Intensity	0.7	8.5	4.6
Number of lines	6	6	12
Penumbral displacement	+0.028 A	−0.001 A	+0.015
Equatorial velocity	1.968±0.003	1.972±0.007	1.970±0.004 (lines) ±0.010 (plates)

Seven of the foregoing plates taken on cloudy or hazy days, yield:

Equatorial velocity	1.909	1.939	1.924 km per sec.

TABLE VII

SOLAR ROTATION, λ 5600

Ottawa, December 6–12, 1910, 32 observations

	Mean	Mean	Mean
Intensity	1.6	6.2	3.9
Number of lines	5	5	10
Equatorial velocity	1.930±0.006	1.936±0.002	1.933±0.003 (lines) ±0.005 (plates)

indicating range in level in the reversing layer (Evershed and St. John).[1] If Adams' hypothesis of increasing angular velocity for increasing elevation in the sun be true, there should be a considerable difference between the velocities of rotation from these two groups of lines. There is no appreciable difference, however, and the results of Table VII show this also. We are thus forced to abandon the level hypothesis, or else to modify it by adding the idea of variability. From the seven plates of Table VI taken on days when the spectrum of the haze was stronger than for the other

[1] Evershed, *Kodaikanal Observatory Bulletin*, **15**, 1909.

St. John, *Mt. Wilson Contr.*, Nos. 69, 74; *Astrophysical Journal*, **37**, 322, 1913; **38**, 341, 1913.

plates, it is seen that there is a difference between the determinations of velocity of the two groups of lines, of 0.030 km per sec.—a difference explainable by the spectrum of the haze blending with the spectrum of the limb. The mean value of the December determinations (Table VII) is smaller by 2 per cent than the value from the July determinations (Table V), possibly owing to the lower declination of the sun in December and to the lower mean intensity of the lines, as well as to the probably greater relative strength of the sky spectrum in December than in July.

SOME GENERAL DISCUSSIONS

It has been mentioned that observers during 1909–1913 found little difference for different lines. Can this be due to the fact that at sun-spot minimum there is less danger from the error due to haze than during sun-spot maximum, pointing either to the presence of varying quantities of matter about the sun or to varying haziness in the terrestrial atmosphere caused by the variation in its ionization accompanying the spot-activities? In most of these 1909–1913 observations the lines were not considered in groups as to difference in intensity, but rather with regard to the element producing the line—in accordance with the recommendations of the Solar Union in 1910—the important relationship between penumbral displacements and intensity and level[1] not having been fully developed at that time. It would seem advisable to investigate the published results from this point of view. This has been done in a preliminary way by the writer. Some results show no appreciable relationship of velocity with line-intensity, some show evidence of this, and some seem to indicate the reverse of what would be expected from Adams' level hypothesis, i.e., a lower rate of rotation with increasing level, a physically possible and quite probable state of affairs. Some exceptions to the level hypothesis are readily explained on assumption of blended spectrum of haze, e.g., λ 4287.566 of intensity 1 at the center of the solar disk is strengthened and widened at the limb, and it has a penumbral displacement of 0.026 A; if this is interpreted as meaning low level, it is to be expected on the level hypothesis that this line

[1] *Ibid.*

should give a lower rotational value than the mean. Adams and Lasby find[1] in 1908 that this line has an equatorial velocity 0.004 km per sec. above the mean; this is explainable by the fact that this line is strengthened, not weakened, at the limb and therefore should yield a larger value than the mean of the other lines which are for the most part weakened at the limb, if the spectrum of the haze is of sufficient strength. In those measurements the lines that are weakened at the limb show a mean residual of -0.003, while the lines that are strengthened at the limb show a residual of $+0.005$ in the mean, indicating a slight effect of sky spectrum. Similar means, -0.002 and $+0.005$, occur in the 1906–1907 series. All published results should be discussed fully from this point of view so that a correction can be made in the absolute values. A knowledge of the behavior of the lines at the limb is essential. Is it possible that the results (4) can be due to chance selection of the lines, so that at one end of the plate the lines will yield a smaller value of the rotation than do the lines at the other end? A cursory examination of Hubrecht's results would make this seem a possible explanation. It is assuredly not a physical effect depending on wave-length, for, if it were, there should be profound differences between series taken at widely different parts of the spectrum, and this is not the case. It may possibly be due to uneven illumination of the grating and one end of the plate being slightly out of focus. It is possible, too, that Hubrecht's result (3) may also be due to blended spectrum of the haze inasmuch as the wave-lengths in the latter are not midway between those from opposite limbs, which would result in effects of blending of different magnitude for the two limbs. It seems to the writer that many of these puzzling differences will vanish when accurate determinations of the effects of the spectrum of the haze are made. A later communication will deal with the effect in various series of observations.

SUGGESTIONS FOR FUTURE OBSERVATIONS

In the meantime it is necessary for all observers to pay special attention to the influence of the spectrum of the haze; it may be eliminated by the exact correlation of changing values of the solar

[1] See footnote 1, p. 177.

rotation with differences in value for different intensities of lines, say from two groups of lines, one greatly weakened at the limb and the other not weakened at the limb. The λ 5200 region offers the best chance for such measurement, since the strongest lines there are quite measureable, and it is possible to eliminate instrumental and other errors by using when desired either iodine or chlorine comparison spectra (as suggested by the writer[1] in 1910 and 1911 and employed by him since the installation of the limb and center prism apparatus in 1913). For these reasons I would suggest that it be considered as a common region even in preference to the λ 4250 region formerly chosen.

In measurements of line-displacements in spots, comparisons of spectra from limb and center, etc., differential effects depending on line-intensity may serve, as for rotation, in eliminating the effects of scattered light; these questions will be discussed in future communications.

CONCLUSIONS

The main conclusions from the foregoing investigation are:

1. Spectrum of haze, probably altogether terrestrial in its origin, accounts for much of the variation in the values of the solar rotation obtained by various observers at different times. Variations hitherto ascribed to the sun appear to be due to variations in scattered light.

2. Spectrum of haze, being different in character to spectrum of limb depending in general on the intensity of the line, blends with spectrum of limb in such a way as to make it appear that different spectral lines yield different values for the velocity of rotation of the sun. Such differences found in measures of the solar rotation at Mount Wilson and at Ottawa are satisfactorily explained in this manner, and it seems possible to dispense with Adams' level hypothesis.

Solar Physics Division
Dominion Observatory, Ottawa
April 1916

[1] De Lury, *Report of the Chief Astronomer, Ottawa*, 1910, p. 168; 1911, p. 293.

THE VARIABLE NEBULA N.G.C. 2261

By EDWIN P. HUBBLE

Recent astronomical research has been especially fruitful in the study of nebulae—a study which has now extended into the realms of dynamics. The spectroscope, with its disregard for the vast distances involved, has reaped, first—radial velocities of planetary, irregular, gaseous, and spiral nebulae; it has also shown internal motion in the great nebula of Orion, and rotation in both spiral and planetary nebulae. Patiently accumulated photographs are just beginning to be of service, as witness the proper motions of nebulae lately announced by Wolf of Heidelberg.

A striking instance of actual change in form has been found[1] in the case of the nebula N.G.C. 2261 (R.A. 6^h32^m, Dec. $+8°51'$, Epoch 1860.0, H. IV 2=h 399=G.C. 1437), one of the few real examples of cometary form in the sky and easily the finest of them. Photographically it is well defined and has almost the form of an equilateral triangle with a sharp stellar nucleus at the extreme southern point. There are faint extensions from the northern portion of it. One long streamer which projects from the northern edge extends almost due north.

Plates taken by the writer in the past winter with the 24-inch reflector of this observatory, when compared under the blink comparator with an unusually good plate taken with the same instrument by F. C. Jordan in March 1908, show changes of outline and displacements of the structural details of the nebula.

These changes, though striking, seemed improbable on account of the short interval—less than eight years—and raised a suspicion as to whether the changes could be real and were in the nebula itself or whether they might not be due to some peculiar photographic action. But repeated plates taken under different conditions of seeing, exposure time, aperture, etc., verified the changes beyond question. One of these tests was to make three successive

[1] A preliminary notice was published in the *Proceedings of the National Academy of Sciences*, **2**, 230, 1916.

exposures of half, double, and the full normal time. These, when compared among themselves, did not show any change except that due to the regular building up of the image. Each of these, however, when compared with the early plates, confirmed the curious changes.

Notwithstanding the excellence of Jordan's plate, its perfectly round star-images and clear-cut nebular details, it became of first importance to find another early plate for confirmation. A reproduction was found in *Knowledge*, **24,** 181, 1901, of a photograph taken at Starfield, January 27, 1900, by the late Dr. Isaac Roberts, with his 20-inch reflector of 100 inches focal length. At the request of the director of this observatory, Mme Dorothea Roberts had the great kindness to prepare and send both positive and negative copies of this invaluable piece of evidence. Long exposure had burned out some of the finer details, but happily sufficient were in evidence to fully confirm the shifts already observed. In the *Lick Observatory Bulletin No. 248*, H. D. Curtis described a photograph of this nebula which he had taken on January 31, 1913, with the 36-inch Crossley reflector with an exposure of two hours. Director Campbell has very kindly loaned us the original negative. It is of remarkably fine quality.

An attempt was made to photograph the nebula with the 40-inch refractor, but the disadvantages of a small focal ratio, 1 to 19, and a visual color-filter, were so great that an exposure of four and three-quarter hours on a brilliantly clear night registered only the nucleus and a trace of the bright band just above. Again at the request of our director, Professor Schlesinger, director of the Allegheny Observatory, very kindly had a plate taken with an hour's exposure with the 30-inch Thaw photographic refractor. The plate was taken by F. C. Jordan, and has sufficient scale to show the brighter details in their true form—coiled streamers running out from the condensed nucleus.

The nucleus of the nebula has long been known as an irregular variable star, R Monocerotis, for which a range from magnitude 9.5 to 13 has been reported. Lassell states that it is not a star, but a true nucleus, such as that of the great spiral in Andromeda, and Barnard has confirmed this opinion by visual observations

with the 40-inch refractor. The longer exposures, especially that of the Lick plate, show a very considerable nebulosity about the nucleus.

The photographs show no indication of variability of the nucleus. The writer has taken eighteen plates which cover a period of five months in the winter of 1915–1916, and three others were taken in 1900, 1908, and 1913, respectively. Small changes might easily be masked by the surrounding nebulosity and the short focus of the reflector, but there are no large differences on the dates mentioned. Such an investigation, however, belongs properly to the field of visual observation or of instruments with a long focus, and the foregoing negative results cannot be considered as conclusive. It is unfortunate that data on so interesting an object should be so scanty. Observations made at Harvard by Leon Campbell and others in the years 1904–1910 indicate a variation through two magnitudes, from 10.0 to 12.0.

Photographically, the nucleus has been about seven-tenths the way from star No. 44 to No. 73 on the Hagen chart; photo-visually, about one-third the way from No. 44 to No. 62, or 10.8 on Hagen's scale and 12.0 on the Harvard scale.

For a study of details in the nebula itself, five negatives were employed (Table I). All save the last were made with reflectors. Negative copies were made of Nos. 1, 3, and 5, reduced to the scale of the 24-inch Yerkes reflector, and the entire set was compared in the blink comparator.

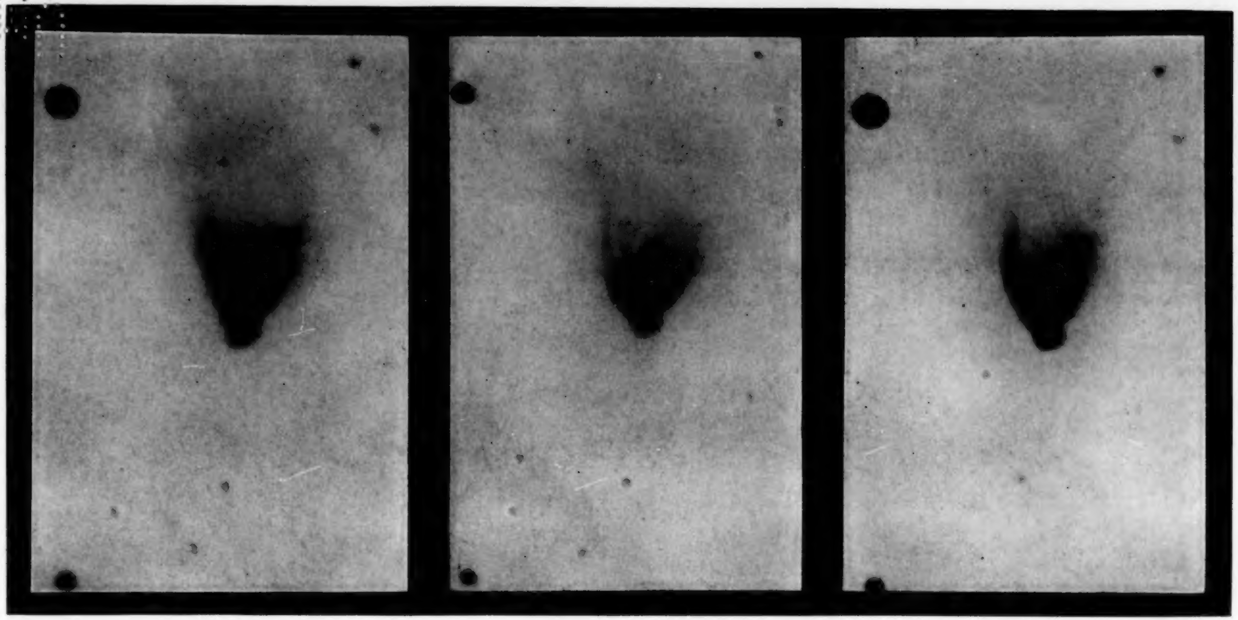
TABLE I

	Date	Aperture	Focus	Exposure	Observatory	Taken by	Notes
		in.	in.				
1	1900 Jan. 27	20	100	90^m	Starfield (England)	I. Roberts	Copies, details blurred
2	1908 Mar. 20	18	93	60	Yerkes	F. C. Jordan	Good
3	1913 Jan. 31	36	210	120	Lick	H. D. Curtis	Good
4	1916 Mar. 8	18	93	70	Yerkes	E. P. Hubble	Good
5	1916 Mar. 11	30	556	60	Allegheny	F. C. Jordan	Weak

The most striking change was what at first appeared to be a transverse shift of the bright band across the nebula just north of the nucleus, and marked *A* on the sketch. A careful examina-

PLATE V

Scale: 1 mm = 3'.0



1908 March 20
Yerkes 24-inch Reflector
Enlarged 24 times

1913 January 31
Lick 36-inch Crossley-Reflector
Enlarged 9 times

1916 March 8
Yerkes 24-inch Reflector
Enlarged 24 times

N.G.C. 2261

tion showed that the following end of *A* is coincident on plates 1 and 2, and also on plates 3, 4, and 5, but between the two sets there is a difference of about 4″.5, in the sense that between 1908 and 1913 an extension appeared on the following edge of the band. The phenomenon is very conspicuous, and is evident in Plate V accompanying this article. Plates 3 and 5 with their larger scales show that this is due rather to the sudden appearance of a mass of nebulosity than to motion of the band itself. This new mass is apparently separated from the band, and is situated about the same distance from the nucleus, on the narrow streamer which connects the head to the body of the nebula. A new branch continues from this mass to meet the point of *C*, and another curves up and to the left, eventually mingling with the streamer which forms the following edge of the nebula, marked *B* on the sketch.

There are several other differences between the negatives which seem to be changes in the nebula itself. On the Starfield plate the north following corner of the triangle is much denser than on the others, and this apparently progresses in the sense that *B* and *D* are shifting their center of density toward the head. Considerable faint nebulosity shows around the north preceding corner and steadily drifts, as one proceeds from plate to plate, toward the center in a south following direction. The preceding end of *A* is coincident on plates 1 and 2, but from 2 to 3, and more markedly from 2 to 4, it shifts along the band toward the east.

The fainter extensions to the north of the triangle show no certain changes, nor do two extremely faint streamers running from the head to the southeast and south by southwest, respectively. In the southeast streamer, however, is a tiny mass of nebulosity, marked *H* on the sketch, so small that it appears on the short-focus plates as a star of about the sixteenth magnitude,

which exhibits a decided and irregular motion. It is very near the nucleus and seems to be covered on plate 1 by the large image of the nucleus. On plate 2 it appears clearly, just on the edge of the image of the nucleus. On plate 3 it has moved in toward the nucleus some 2".5 of arc, so that on plate 4 it lies within the image. Plate 5 has a larger scale and shows it clearly, but apparently coincident with the position on plate 2. That is, this curious bit of nebulosity moved in toward the nucleus just when the new masses appeared in the body; viz., between 1908 and 1913. When the nebula comes around into position this winter, some further light may be thrown on the subject by long exposures with instruments of long focus.

It would seem from the data at hand that *H* has moved not less than 0".5 per year between 1908 and 1913, and possibly much more. From the relation of parallax to proper motion and linear velocity, it follows that the parallax of this object is about $\frac{2.5}{V}$, where V is expressed in kilometers per second. Any velocity, therefore, up to 100 kilometers per second would suggest a sensible parallax, especially as the sharp stellar nucleus permits of accurate measurement. It is to be hoped that the nebula will find a place on the program of some of the instruments suited for such work. Careful measurements of the plates at hand fail to show any appreciable proper motion of the nucleus.

Several possibilities suggest themselves when one is seeking an explanation of the changes. The nebula may be rotating as a whole, bringing new features into view. An objection to this is that the changes are more evident at the edges, whereas a simple rotation would show its greatest effect in the middle. Further, many of the markings in various parts of the nebula show no change whatsoever, and a rotational effect should show a regularity of distribution.

Another possibility is that of local brightening and fading of stationary matter. This would satisfy most of the data, but for certain points, such as *H*, actual motion is too evident to be disregarded. Among these considerations is the current suggestion that a variable nebula might shine by light reflected from the

nucleus and the variation of the two would be directly related. In the case of this nebula, the nucleus is already believed to be irregularly variable, and the nebula might shine by reflected light, but any effects of variability of the nucleus should show a regularity that is entirely absent from the observations. One would be forced to conceive of only certain portions of the nebula being affected.

The most plausible explanation would seem to rest on actual motion of portions of nebulosity relative to the nebula as a whole. The plates indeed suggest a discharge of matter from the nucleus, northward along the following edge, where the band *A* joins to the head. However, the data at hand are too meager for conviction and the explanation must await further study of the nebula with large telescopes.

The position in the sky of N.G.C. 2261 seems highly significant. It lies in, and near the end of, a dark lane which leads up to the nebulosity around 15 Monocerotis, indicating that the nebula is nearer to us than the mass of stars blotted out by the obscuring matter in the lane. This portion of the Milky Way is rich in diffuse nebulosity, nebulous stars, and dark, obscured regions. There is another cometary nebula, N.G.C. 2245, just over two degrees north preceding, again in a dark lane, and so obviously connected with it and with the nebulous cluster, that no great stretch of the imagination is required to place the two cometary nebulae in the same category. They have so much in common that it would not be surprising to find them similar in their peculiarities, and it is to be regretted that we have no old plates of N.G.C. 2245 to compare for change.

The case is strengthened by the data from other variable nebulae. Hind's variable by T Tauri (N.G.C. 1555) is the most famous. Its remarkable career has been carefully investigated by Barnard in two papers published in *Monthly Notices*, **55**, 442, 1895, and **59**, 372, 1899. Some sixty years ago, it was a conspicuous object in a small telescope. Today it is barely discernible with the best instruments. Recent long-exposure photographs show an exceedingly faint, fan-shaped wisp of nebulosity, close to and pointing toward the variable T Tauri, which Burnham and Barnard saw as a small condensed nebula. It also is situated in a dark lane.

Schmidt, at Athens, discovered in 1861 a small nebula just beside the variable star R Coronae Australis. It is now known as N.G.C. 6729. He later announced it as a variable nebula, and Innes at the Cape in 1890 confirmed Schmidt's observations. Very recently Knox-Shaw at Helwan made a study of the nebula and removed any doubts as to its variability by photographic evidence. In this case also there is a fan-shaped wisp with a variable star at the tip. Again the variable lies in a very pronounced dark region south following the globular cluster N.G.C. 6723. Knox-Shaw read a paper on the subject before the British Astronomical Association, which is reported in the *Journal* of that association for June 1916. He affirmed that the nebula varies from week to week both in brightness and in shape. No definite period has been found for either star or nebula.

There are two other cases of variability within nebulae. Just north preceding N.G.C. 6729, and in the very heart of the dark region, is a wide double star, each component of which is the nucleus of a considerably large and bright mass of nebulosity. Innes, in a recent circular of the Union Observatory, announced that one of the nuclei is variable. The other case is that of the planetary N.G.C. 7662, the nucleus of which Barnard has observed to vary through several magnitudes. The nebula, of course, is gaseous, but the nucleus gives a strong, continuous spectrum. As a planetary, it differentiates itself from the fan-shaped nebulae.

Several plates of N.G.C. 2261 were taken here with a 15° objective-prism on the Zeiss U. V. camera. The nebula gives a strong, continuous spectrum, in which no lines were to be seen, but which, as compared with the neighboring stars of early type, weakened toward the violet, after the fashion of a spectrum of the solar type. This explains why the nebula photographs so readily with a visual color-filter: for while, with a visual color-filter and a Cramer Instantaneous plate, the usual equivalent exposure with the 24-inch reflector is about five times that for a free exposure with a Seed 30 plate, in the case of this nebula, about two and a half times the normal free exposure sufficed to give a strong image through the color-filter. N.G.C. 2245 was in the camera field and also gave a good continuous spectrum. This latter nebula is so

obviously connected with the nebulosity around the cluster, Dreyer Index Cat. 2169, that it is a fair inference to suppose that nebulosity also has a continuous spectrum. This is borne out by the speed with which it registers through the visual color-filter. The variable nebulae would seem to form a family group, characterized by the shape more or less of a fan, with a condensed variable nucleus at the tip, and having some connection with dark regions in the sky. It would be of interest to determine the nature of R Coronae Australis, whether it is not in reality a nucleus rather than a true star.

North of the nucleus of N.G.C. 2261 about 97″, and preceding it by 4ˢ4, is a fifteenth-magnitude star, marked *P* on the sketch, which has a proper motion of 27″ per century in a direction 164°. North following 9′ and 10′, respectively, are two variable stars whose maxima are at about 15.5 mag. There is still another variable some 17′ north preceding the nucleus, with a range of at least from magnitude 11 to 17.

Yerkes Observatory
September 14, 1916

Minor Contributions and Notes

NOTE ON A SUPPOSED VARIATION IN THE SOLAR ROTATION

In a recent number of this *Journal* is published a paper entitled "A Variation in the Solar Rotation," in which the conclusion is reached[1] "that the sun, during the summer of 1915, underwent a cyclic variation in its rotation rate with a range of 0.15 km. This variation was completed in about a month." This result appeared to me to be another case showing the effect of an overlapping spectrum of haze such as was discussed in my paper (see pp. 177–179 of this number). The observations were made with the same equipment as I have been using day by day since 1913 for the purpose of investigating any changes which might occur in the positions of lines of limb and center, so it happened that I made many observations in various regions of the spectrum during the period of the observations described. The record shows that in general high values of the rotation in the observations mentioned were obtained on the brighter days and low values on the hazier days. Selecting plates at λ 4250 on July 13 (seven double observations), and on July 20 (five double observations), on which dates the measurements mentioned above show the lowest and highest values, I measured λ 4226.9, Ca, 20, strengthened at the limb, and λ 4225.6, Fe, 3, and λ 4232.8, Fe, 2, both weakened at the limb, with results and comparisons as follows:

	July 13, Hazy	July 20, Bright
	km per sec.	km per sec.
H. H. Plaskett's values for five lines of intensities 3 to 8, λ 5900	1.846	2.026
De Lury's values:		
4225.6, Fe, 3	1.712	1.966
4226.9, Ca, 20	1.794	1.983
4232.8, Fe, 2	1.711	1.972
Difference between Ca line and Fe lines	0.082	0.014

[1] H. H. Plaskett, *Astrophysical Journal*, 43, 156, 1916.

These measurements show three results, which are all explainable by the blending of the spectrum of haze with that of the solar limb: (1) The values of the solar rotation are smaller on the hazy day than on the bright day. (2) The difference between the values for weak and strong lines is greater on the hazy day than on the bright day. (3) The values at the greater wave-length, λ 5900, are greater than those at the smaller wave-length, λ 4230, the spectrum of haze being stronger relatively to the spectrum of the limb for smaller wave-lengths than for the greater wave-lengths.

The values at λ 4230 point to a value for the equatorial velocity of about 2.03 or 2.04 km per second for a zero difference between the values for weak and for strong lines.

Measurements of the λ 5900 plates for groups of weak and strong lines will no doubt confirm the conclusion that the variation in question is due entirely to variations in the terrestrial haze.

RALPH E. DE LURY

SOLAR PHYSICS DIVISION
DOMINION OBSERVATORY, OTTAWA
August 1916

NOTICE

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Articles written in any language may be accepted for publication, but unless a wish to the contrary is expressed by the author, they usually will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right unless the author requests that the reverse procedure be followed.

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